VOLUME LIV DEC 5 1921 NUMBER 4

ASTRON. OBS.

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

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NOVEMBER 1921

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THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

THE CAMBRIDGE UNIVERSITY PRESS, London
THE MARUZEN-KABUSHIKI-KAISHA, Tokyo, Osaka, Kyoto, Fukuoka, Sendai
THE MISSION BOOK COMPANY, Shanghai

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The following are authorized to quote the prices indicated:

For the British Empire: The Cambridge University Press, Fetter Lane, London, E.C. 4. Yearly subscriptions, including postage, 43*s.* each; single copies, including postage, 5*s.* 6*d.* each.

For Japan and Korea: The Maruzen-Kabushiki-Kaisha, 11 to 16 Nihonbashi Tori Sanchome, Tokyo, Japan. Yearly subscriptions, including postage, Yen 13.30 each; single copies, including postage, Yen 1.73 each.

For China: The Mission Book Company, 13 North Szechuen Road, Shanghai. Yearly subscriptions, $6.00; single copies, 75 cents, or their equivalents in Chinese money. Postage extra, if mailed direct outside of Shanghai, on yearly subscriptions 62 cents, on single copies 11 cents.

Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit.

Business correspondence should be addressed to The University of Chicago Press, Chicago, Illinois.

Communications for the editors and manuscripts should be addressed to the Editors of THE ASTROPHYSICAL JOURNAL, Ryerson Laboratory, University of Chicago, Chicago, Illinois.

The cable address is "University, Chicago."

The articles in this Journal are indexed in the *Readers' Guide Supplement*, New York, N.Y.

Entered as second-class matter, January 17, 1895, at the Post-office at Chicago, Ill., under the act of March 3, 1879.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 13, 1918.

PRINTED IN THE U.S.A.

THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME LIV NOVEMBER 1921 NUMBER 4

THE DEFINITION OF A NOVA

By J. G. HAGEN, S.J.

ABSTRACT

Collision theory of the origin of novae, irregular variables, O stars, planetary nebulae and δ Cephei variables.—Seeliger's suggestion that temporary stars originate from *encounters between stars and cosmic nebulae* is made more specific by assuming that the nebulae are cometary—that is, become luminous at the approach of the stars, and the possible results of four types of such encounters are discussed. (1) Transit without contact might produce a nova with a relatively small range of variation (type T Boötis ?). (2) Grazing the nebula, if repeated occasionally, might result in an irregular variable such as T Pyxidis. (3) Passage through the nebula on a hyperbolic path might result in a nova of the ordinary type (T Aurigae) and in a star with a nebulous envelope, an O star. (4) Capture of the star by the nebula might give a δ Cephei variable or a planetary nebula. The theory is shown to account for nearly all the facts of observation relating to ordinary novae, particularly the range of light, shape of the light-curve, character of the spectrum, their rarity, and their physical similarity to O stars and planetary nebulae.

Definition of a nova suggested by the above theory is "a cometary nebula brought temporarily into close proximity or contact with a bright star." This definition does not include novae in spiral nebulae, but fits the four types enumerated.

That the definition of new stars, so called, will have to be revised has been repeatedly expressed in recent publications. It is quite natural that Newton's definition should have held its own for two hundred years, because only the spectroscope could reveal new facts about these stars.

In his *Principia mathematica* (ed. 1760), III, last proposition, Newton defines the novae as "fixed stars that suddenly appear, at first shine brilliantly and then gradually fade away." Later

definitions, like those of Newcomb[1] and Miss Clerke,[2] are but expansions of that given by Newton.

I

In formulating a definition that takes account of what we now know about nebulae surrounding the novae, about stars of Class O and planetaries, it will be convenient, if not necessary, to start from certain assumptions that may yet be disputed. The resulting theory, although not definite, can for the present at least serve as a working hypothesis.

One of these assumptions is that temporary stars originate from encounters between stars and cosmic clouds, an opinion proposed and elaborated by Seeliger, in *Astronomische Nachrichten*, **181**, 81, 1909, and in other communications as far back as 1886. Another assumption consists in the views expressed by the writer in an article on the "Astrophysical Problem of Variable Stars"[3] and, in particular, in the view on the δ Cephei problem. We shall only recall from that article, that a δ Cephei variable may be considered as a binary system, one component of which is a star like our sun and the other a cosmic nebula of cometary qualities. A nebula is said to have "cometary qualities" when it becomes luminous by the mere approach to a star like our sun.

Seeliger's assumptions regarding star and cloud are quite general and exclude no special case. We now specify his "cloud" as a cometary nebula that will develop eruptions of light by the mere approach of a radioactive star similar to our sun. A clear basis is thus obtained for further conclusions on the nature of temporary stars.

II

To begin with, it seems necessary to exclude from our consideration the new stars found in spiral nebulae because, judging from the continuous spectrum of S Andromedae, the nova of 1885, they form a class of their own.

The light-curves of the novae are so much like those of the δ Cephei type that the comparison will be suggestive in many

[1] *The Stars*, p. 127.

[2] *Problems in Astrophysics*, p. 375.

[3] *Monthly Notices of the Royal Astronomical Society*, **81**, 226, 1921.

ways; there are only two differences: the light-curves of the novae have a larger range, amounting sometimes to fifteen magnitudes, and have no periodic repetition.

The range of variation in the δ Cephei stars is confined to about one magnitude, and yet they are known to be giant stars. What, then, must be the dimensions of a nova? Campbell and Moore have found evidence that planetary nebulae, which we hope to show to be a special class of novae, contain sufficient material to form systems more extensive than our solar system.[1]

The periodic variation of the δ Cephei stars consists essentially, as we have assumed, in the elliptic motion of two components. Now substituting other kinds of orbits, regular or disturbed, we may get temporary variables. Divers hypotheses can be made.

1. If a star passes by the nebula in a relatively hyperbolic orbit, without contact, one maximum brightness is produced, exactly similar to that of a δ Cephei variable, but without repetition. Temporary stars of this class easily escape observation, even when the eruption of light takes place on our side of the nebula, because of the small range of variation and the short-lived eruption.

May not Baxendell's T Boötis (1860) or Pogson's U Scorpii (1863), which reached the tenth and ninth magnitudes respectively, and other merely telescopic novae, belong to this class?

2. What will happen when the star just grazes the cosmic nebula may perhaps be learned from irregular variables like P Cygni, T Tauri, and T Pyxidis. The first of these had reached the third magnitude in 1600 and a second time in 1657–1659; since then it has remained a star of fifth magnitude. T Tauri was of the ninth magnitude in 1852 and again in the years 1877–1881 and 1902; according to the *Annual Report* for 1915 of the Mount Wilson Observatory (No. 61, p. 291) the star is surrounded by an extensive atmosphere which shows the emission lines of the O spectrum. Of T Pyxidis only three outbursts were noticed in thirty years, viz., in 1890, 1902, and 1920. The last one was observed spectroscopically with the 100-inch reflector by Adams and Joy, who found numerous relationships to the spectrum of novae.[2]

[1] *Publications of the American Astronomical Society*, **3**, 195, 1918, and *Publications of the Lick Observatory*, **13**, 177, 1918.

[2] *Popular Astronomy*, **28**, 514, 1920.

Stars of this kind form a transition from the δ Cephei type to the novae properly so called.

3. Elliptic motion between star and nebula may become impossible when the star's mass, relative to that of the nebula, exceeds the limits compatible with the δ Cephei type. Indeed, mutual attraction may then become so strong that the star gets enveloped in the nebula. If its velocity relative to the nebula is sufficiently large to overcome the resisting medium and the two bodies separate in a hyperbolic orbit, we have a temporary star of the ordinary type, B Cassiopeiae, T Aurigae, and others.

This theory is put to the severe test of having to account for the range of light, for the character of the spectrum, and for the shape of the curve, but it seems to stand it.

a) The range has been explained by Professor Seeliger and the spectrum by Dr. Halm, both on the hypothesis of a (dark) celestial body entering a cosmic cloud. Now their explanations of the general case seem to be even facilitated when the body entering the cloud is specified as a star possessing all the radiant energy of our sun and the cloud as a nebula endowed with the cometary quality of becoming luminous by the mere approach to the radiating star.

While in a δ Cephei star, at periastron passage, the intensity of light is about doubled, that of a nova may be increased a million fold. According to Seeliger the mechanical impact alone, between star and cloud, is amply sufficient to account for a range like this. So much the more will, in our case, the combined effect of radiation and friction account for it. Examples worked out numerically are given by Veronnet in *Comptes Rendus*, **172**, 666, 1921. He calculates the surface temperature of a nova on various suppositions regarding the orbits, masses, densities, radii of star and nebula, and he shows how the mechanical theory is by itself apt to satisfy the observations. If we ever had the opportunity of observing a comet falling into the sun, we might be able to estimate the other factor of the process also, the radiation within the nova.

b) About the spectrum and its variations in temporary stars Dr. Halm has written an extensive treatise[1] in which he shows at

[1] *Proceedings of the Royal Society of Edinburgh*, **25**, 513–552, 1905; see especially p. 519.

least the possibility of explaining all the facts, provided the additional hypothesis is made that the star, in leaving the cloud, carries with it a quantity of nebulous matter. For a cosmic cloud specified as a cometary nebula this additional assumption is not only natural but apparently inevitable. There are thus two stages to be distinguished in a nova of this class: the initial stage of a giant nebula with a brilliant stellar nucleus, and the subsequent stage of a star surrounded by a nebulous atmosphere. The star has become an O star, entirely separate from the large cloud, and the latter will gradually fall back into its former obscurity. The O star remains, but the nova has disappeared.

Without entering into details, we quote a suggestion of Adams and Pease,[1] "that the disappearance of the chief nebular lines is coincident with the emergence of the star from the nebula."

c) The light-curve of a nova presents no difficulty to the theory. The varieties among some of the curves in the ascending branch may in part be due to the direction from which the star enters the cloud, relative to the line of sight. Suppose the star enters the nebula from our side, the process of illumination, preceding actual contact, becomes visible. It will, on the contrary, be partly hidden when the approach is from the averted side.

The passing of the star through the cloud must disturb the surface equilibrium of the nebula, which can only be restored through a series of oscillations. The descending branch of the light-curve discloses the disturbance by its undulating shape. It is for this stage of a nova that the pulsation theory would seem to find its full application.

4. If the star, after entering the nebula, does not leave it in a hyperbolic orbit, it is bound to become permanently captured by it. Even if it should escape and begin to describe an elliptic arc, it must re-enter the cloud and, in a spiral-shaped path, reach the center of gravity. When the two celestial bodies move in directions that form an acute angle, their relative velocity is partly the difference of their proper motions and may be so small that the star cannot overcome the resisting medium of the nebula; it has become its permanent nucleus.

[1] *Astrophysical Journal*, **40**, 297, 1914.

Professor Campbell asks the question[1] whether planetaries and novae are "results of catastrophes" and suggests "a common or closely related origin of the two classes of objects." Why not say directly that the planetary nebula originated as a nova of the kind here considered?

According to this theory the difference between O stars and planetary nebulae is mainly one of quantity. The O star carries with it a portion of the nebula, the planetary is the entire nebula enveloping the star. The similarity was first recognized by E. C. Pickering[2] in 1891, when he combined the spectra of O stars and of planetary nebulae into Class V of Secchi's series. Twelve years later W. H. Wright found that the nuclei of some planetary nebulae are O stars, and, vice versa, that the envelopes of some O stars are planetary nebulae,[3] a discovery verified soon after by Bosler[4] and others.

III

The physical connection between novae, planetary nebulae, and O stars maintained in this theory thus accounts satisfactorily for nearly all the facts of observation, but a number of questions remain to be answered.

1. The salient feature of these celestial bodies is their rare occurrence. The number of known planetary nebulae is less than 150 and that of the O stars smaller yet. The ordinary novae are fully as uncommon relatively to the total number of stars. This circumstance has long since led to the view that the three classes of objects do not fit into the general path of natural evolution and must be considered as products of exceptional events. The fact that all of them are galactic phenomena lends support to this view.

The "exceptional events" must be the encounters between stars and nebulae, as explained above.

2. If a planetary originates from a star like our sun entering a giant nebula, the question may be raised as to the mass of a plane-

[1] *Publications of the Lick Observatory*, **13**, 173, 1918.

[2] *Astronomische Nachrichten*, **127**, 5, 1891.

[3] *Astrophysical Journal*, **40**, 466, 1914.

[4] *Comptes Rendus*, **160**, 124, 1915.

tary. Fortunately, the question has been answered by Professor Campbell. From the interior rotations of the larger and brighter nebulae he deduced that their minimum probable masses are several fold the sun's mass, while smaller planetaries may be comparable with, or even smaller than, our solar system.[1]

More serious perhaps is the question of color. No yellow light reaches us from the nucleus of a planetary, either visually or photographically, in contrast to spiral nebulae, whose nuclei are of the solar type and the branches intensely blue.[2] However, a conclusion from one of these essentially different classes of objects to the other is not warranted. Nor do we know what transformations a radioactive star undergoes when permanently imbedded in a cometary nebula.

The radial velocity of planetary nebulae, though in general of the same order of magnitude as that of the stars, is on the average more than twice as large.[3] The conclusion that cometary nebulae, as a class, move faster than stars would seem premature, because the five δ Cephei stars, contained in Voûte's *First Catalogue of Radial Velocities* (1920), have a mean velocity of only 13.4 km. The explanation is rather this, that the chances for collision are the greater, the greater the speed of individual stars and nebulae.

This view is not contradicted by the fact that the novae so far examined have small angular proper motions,[4] because stars that encounter nebulae with nearly opposite velocities and work their way through a resisting medium must necessarily lose part of their proper speed, angular or radial. The case is different from that of planetaries, in which the initial velocities of star and nebula are more or less parallel and are fused into one common motion.

IV

Recapitulating, we have the following classes of so-called new stars. First, the novae in spiral nebulae, excluded from our theory (type S Andromedae). Regarding those within our stellar

[1] *Publications of the Lick Observatory*, **13**, 178, 1918.

[2] F. H. Seares, *Publications of the American Astronomical Society*, **3**, 220, 1918.

[3] *Publications of the Lick Observatory*, **13**, 72.

[4] *Popular Astronomy*, **29**, 221, 1921.

system, some originate without actual contact between star and nebula and are rarely noticed (type T Boötis?). Others burst out through the occasional grazing of a star and a nebula which, at least for a time, are both physically connected (type T Pyxidis?). Still others, perhaps most of them, become O stars (type T Aurigae). Finally, some will turn into planetary nebulae (no type assignable because the transformation has not yet been directly observed).

Considering these various possibilities, we can understand why an unequivocal definition of temporary stars has hitherto been impossible. Restricting the concept of a new star to the outburst of light, and not comprising in it the permanent stages of planetaries and of O stars, the following definition would seem to cover all the cases within our stellar system: *A nova is a cometary nebula brought temporarily into close proximity or contact with a bright star.*

VATICAN OBSERVATORY, ROME
June 1921

INVESTIGATIONS ON PROPER MOTION

FOURTH PAPER: INTERNAL MOTION IN THE SPIRAL NEBULA MESSIER 51[1]

By ADRIAAN VAN MAANEN

ABSTRACT

Spiral nebula Messier 51.—A comparison of a plate taken by Mr. Duncan on April 8, 1921, with one taken by Mr. Ritchey on February 7–8, 1910, both at the 25-foot focus of the 60-inch reflector, enabled the *proper motion of the nebula* and the relative motion of its parts to be determined. Measurements of 80 points of the nebula compared with those of 20 stars give for the nebula an annual proper motion of +0".006 in right ascension and +0".001 in declination. The *internal proper motion* is not a pure rotation since the mean radial component is outward and is 42 per cent of the mean tangential component which is 0".019 ENWS; rather it is a spiral motion out along the arms at the rate of 0".021 per year together with a slight outward radial motion of 0".003.

Two sixteenth magnitude stars with large proper motions, about 0".15 per year, were found *near Messier 51*. They are called *f* and *r*.

Five years have elapsed since the first evidence of internal motion in a spiral nebula, as derived from direct photographs, was announced in this *Journal*.[2] The time interval between the old and new plates taken at the 25-foot focus of the 60-inch reflector has now been doubled, thus quadrupling the weight of the annual motions derived from them; it was accordingly thought worth while to investigate several objects of this class.

The first spiral nebula for which two plates with a ten-years' interval became available was M 33. A note concerning the preliminary measures for 51 points of this nebula has appeared elsewhere.[3] These results show a decided internal motion, which, as in the case of M 101,[2] can be explained either as a rotation combined with a radial motion outward, or as an outward motion along the streamers of the nebula. More elaborate measures of this object await the securing of another plate. If, as is hoped, we can measure several hundred points in this object, some light may be thrown on the laws that govern the motions.

[1] *Contributions from the Mount Wilson Observatory*, No. 213.

[2] *Astrophysical Journal*, **44**, 210, 1916.

[3] *Proceedings of the National Academy of Sciences*, **7**, 1, 1921.

In the meantime Mr. Duncan secured a plate of the spiral nebula M 51, of which Mr. Ritchey had previously taken several photographs. Duncan's plate, taken April 8, 1921, compares most favorably with one secured by Ritchey on February 7 and 8, 1910. Both plates were exposed 3 hours and 55 minutes and are of good quality. Eighty points, presumably belonging to the nebula, were measured, while for comparison purposes 23 stars were selected. Further, two photographs taken by Mr. Seares, one with and one without a yellow color-screen, enabled me to see if objects were included in either category which probably did not belong there. Of the 80 nebulous points only one, No. 27, was decidedly red, and may therefore not be a part of the nebula. In the discussion of the internal motions this point was on this account excluded. Among the comparison stars, on the other hand, one object, *j*, was found to be decidedly blue. As for this reason it may be a part of the nebula, it was excluded for comparison purposes. A rough reduction of the measures showed, moreover, that two of the comparison stars, *f* and *r*, have large proper motions. These were also excluded, leaving 20 comparison stars in all.

The plates were measured with the new stereocomparator—which will be described in another article—in four positions, with the directions east, west, north, and south successively coinciding with that of increasing readings of the micrometer screw.

In order to deal with smaller values in the computations, the mean measured displacements in right ascension and declination, expressed in parts of the micrometer screw, were reduced to displacements in 0".001 per year by multiplication of the factor

$$q=\frac{27200}{31890\times 11.16}=0.0764,$$

in which 27200 is the number of thousandths of a second of arc per millimeter on the plates, 31890 the number of the parts of the micrometer screw per millimeter on the plates, and 11.16 the interval in years between the two plates. The resulting values, m_α and m_δ, may be reduced to annual proper motion by

$$\left.\begin{aligned} m_\alpha &= a+bx+cy+dx^2+exy+fy^2+\mu_\alpha, \\ m_\delta &= a'+b'x+c'y+d'x^2+e'xy+f'y^2+\mu_\delta, \end{aligned}\right\} \qquad (1)$$

TABLE I

CO-ORDINATES AND MEASURED ANNUAL DISPLACEMENTS

No.	x	y	μ_α	μ_δ
a	+0.′4	+1.′6	−0.″036	−0.″006
b	+3.4	+4.3	+ 22	− 4
c	+4.9	+2.7	− 6	+ 8
d	+3.4	+1.3	− 14	− 14
e	+3.7	−3.1	+ 9	+ 15
f	+3.6	−8.1	− 140	+ 38
g	−0.3	−7.3	− 9	− 7
h	+0.6	−3.1	+ 9	− 5
i	+1.2	−2.2	0	− 9
j	+0.5	−2.2	+ 17	0
k	−3.1	−2.4	+ 6	+ 30
l	−2.4	−1.9	+ 10	+ 6
m	−3.9	−0.5	− 32	− 28
n	−1.9	−0.2	+ 28	+ 4
o	−1.1	+0.3	+ 19	− 2
p	−1.2	+0.9	− 14	+ 10
q	−1.5	+2.4	− 8	0
r	−2.5	+2.5	− 159	− 34
s	−4.3	+2.2	+ 12	− 4
t	−0.8	+3.0	+ 9	+ 4
u	−0.8	+4.0	− 3	+ 11
v	+3.7	+1.3	0	− 1
w	+2.5	+0.4	0	− 5
1	+0.5	0.0	+ 28	+ 10
2	+0.6	−0.2	− 21	+ 6
3	+0.5	−0.7	− 13	+ 6
4	+0.6	−0.9	− 12	+ 14
5	0.0	−0.9	+ 4	+ 9
6	0.0	−1.0	+ 9	+ 3
7	−0.1	−1.2	− 25	+ 9
8	−1.0	−0.9	− 1	− 1
9	−1.5	+0.3	− 3	− 19
10	−1.5	+1.3	− 16	− 22
11	−1.3	+1.7	+ 36	− 18
12	−1.0	+2.1	− 8	− 24
13	−0.5	+2.0	+ 16	− 9
14	−0.3	+1.6	+ 23	− 7
15	−0.5	+1.0	+ 23	− 28
16	0.0	+1.0	+ 8	− 9
17	+1.2	+0.5	+ 11	+ 10
18	+1.5	+0.5	+ 22	+ 17
19	+1.4	0.0	+ 28	+ 19
20	+1.9	−0.6	+ 24	+ 16
21	+2.1	−0.7	+ 43	+ 29
22	+1.6	−1.6	− 6	+ 17
23	+1.6	−2.1	− 11	+ 28
24	+1.2	−1.9	− 26	+ 7
25	+1.0	−2.1	− 20	+ 23
26	+1.1	−2.1	− 25	+ 24
27	−2.1	+0.9	+ 8	− 45
28	−2.2	+0.9	− 7	− 21
29	+0.′9	+2.′5	+0.″025	−0.″003

TABLE I—*Continued*

No.	x	y	μ_α	μ_δ
30	+1′.3	+2′.2	+ 0″.14	+0″.008
31	+1.6	+1.9	+ 12	+ 24
32	+1.6	+1.8	− 10	+ 3
33	+1.8	+1.5	+ 21	+ 23
34	+2.5	+0.3	+ 7	+ 23
35	+2.4	+0.2	+ 18	+ 30
36	+2.7	−1.1	+ 19	+ 18
37	+2.4	−2.5	− 8	+ 22
38	+2.1	−3.8	− 1	+ 34
39	+1.9	−4.0	− 9	+ 21
40	+2.0	−4.2	− 6	+ 18
41	+1.6	−5.2	− 25	+ 26
42	+0.6	−0.9	+ 20	+ 5
43	−0.8	−0.9	− 10	− 21
44	−0.9	−0.9	− 5	− 13
45	−1.2	−0.7	+ 5	− 28
46	−2.1	−0.2	+ 16	− 6
47	−1.8	0.0	+ 3	− 33
48	−2.5	+0.6	+ 3	− 17
49	−2.7	+0.3	+ 10	− 24
50	−1.8	+0.5	+ 6	− 29
51	−2.8	+2.4	+ 8	− 25
52	−3.1	+2.1	+ 9	− 16
53	−0.6	+2.4	+ 23	− 25
54	−0.6	+2.4	+ 38	+ 3
55	−0.3	+2.4	+ 34	− 8
56	−0.2	+2.5	+ 40	− 14
57	0.0	+3.1	− 9	− 5
58	0.0	+3.0	+ 18	− 17
59	−0.8	+1.2	+ 22	− 33
60	+1.5	+0.6	+ 11	+ 10
61	+2.0	−0.5	+ 12	+ 34
62	+1.9	−0.8	+ 31	+ 23
63	+1.8	−0.9	+ 6	+ 15
64	+1.7	−2.4	+ 4	+ 39
65	+0.8	−2.2	− 19	+ 9
66	+0.2	−1.9	− 31	− 2
67	0.0	−2.2	− 34	+ 9
68	−2.0	−1.3	− 24	− 12
69	+0.6	+2.8	+ 30	− 17
70	+1.8	+1.9	+ 8	+ 12
71	+2.1	+2.0	+ 14	+ 15
72	+2.1	+1.9	+ 29	+ 15
73	+2.4	+1.8	+ 17	+ 4
74	+2.4	+0.8	+ 44	+ 21
75	+2.4	−0.6	+ 32	+ 27
76	+2.5	−0.6	+ 10	+ 33
77	+2.2	−1.1	+ 4	+ 13
78	+2.5	−2.4	− 27	+ 9
79	+2.4	−2.7	− 11	+ 25
80	+1′.6	−3′.8	0″.000	+0″.020

in which a, b, ... f' are the plate-constants, x and y the coordinates of the objects measured, and μ_α and μ_δ the annual proper motions, expressed in thousandths of a second of arc.

The plate-constants were derived by a least-squares solution from the twenty pairs of equations of the form (1) for the 20 comparison stars. For these objects the usual supposition was made that μ_α and μ_δ are in the mean zero and are not functions of x and y. The constants $a, b, \ldots . f'$ thus found were substituted in the equations of condition (1) of all the objects measured. The resulting annual proper motions are given in the fourth and fifth columns of Table I. The second and third columns of this table contain the co-ordinates in x and y, expressed in minutes of arc with a precision sufficient for identification.

The motions thus derived for the nebular points include the motion of the nebula as a whole with respect to the 20 comparison stars as well as the internal motions of the individual points. To derive the motion of the nebula as a whole, the same process was followed as for M 101.

a) The mean for all of the 79 points gives:

$$\mu_\alpha = +0''.006 \quad \mu_\delta = +0''.004.$$

b) Dividing the points into four groups, corresponding to the four quadrants, the means of the two groups in opposite quadrants should give a good agreement. We find:

$$\text{Means for I and III} \begin{cases} \mu_\alpha = +0''.004 \\ \mu_\delta = 0''.001 \end{cases}$$

$$\text{Means for II and IV} \begin{cases} \mu_\alpha = +0''.006^5 \\ \mu_\delta = 0''.000 \end{cases}$$

The four quadrants combined give:

$$\mu_\alpha = +0''.005 \quad \mu_\delta = +0''.000^5 .$$

c) In order to avoid points far from the center on account of their asymmetrical distribution, we may use only those within a radius of 3′. We then find:

$$\text{Means for I and III} \begin{cases} \mu_\alpha = +0''.004^5 \\ \mu_\delta = +0''.001^5 \end{cases}$$

$$\text{Means for II and IV} \begin{cases} \mu_\alpha = +0''.008^5 \\ \mu_\delta = -0''.001 \end{cases}$$

The four quadrants combined give:

$$\mu_a = +0''.006^5 \quad \mu_\delta = 0''.000.$$

Giving equal weight to each of the three methods used, we derive as the final motion of the nebula as a whole

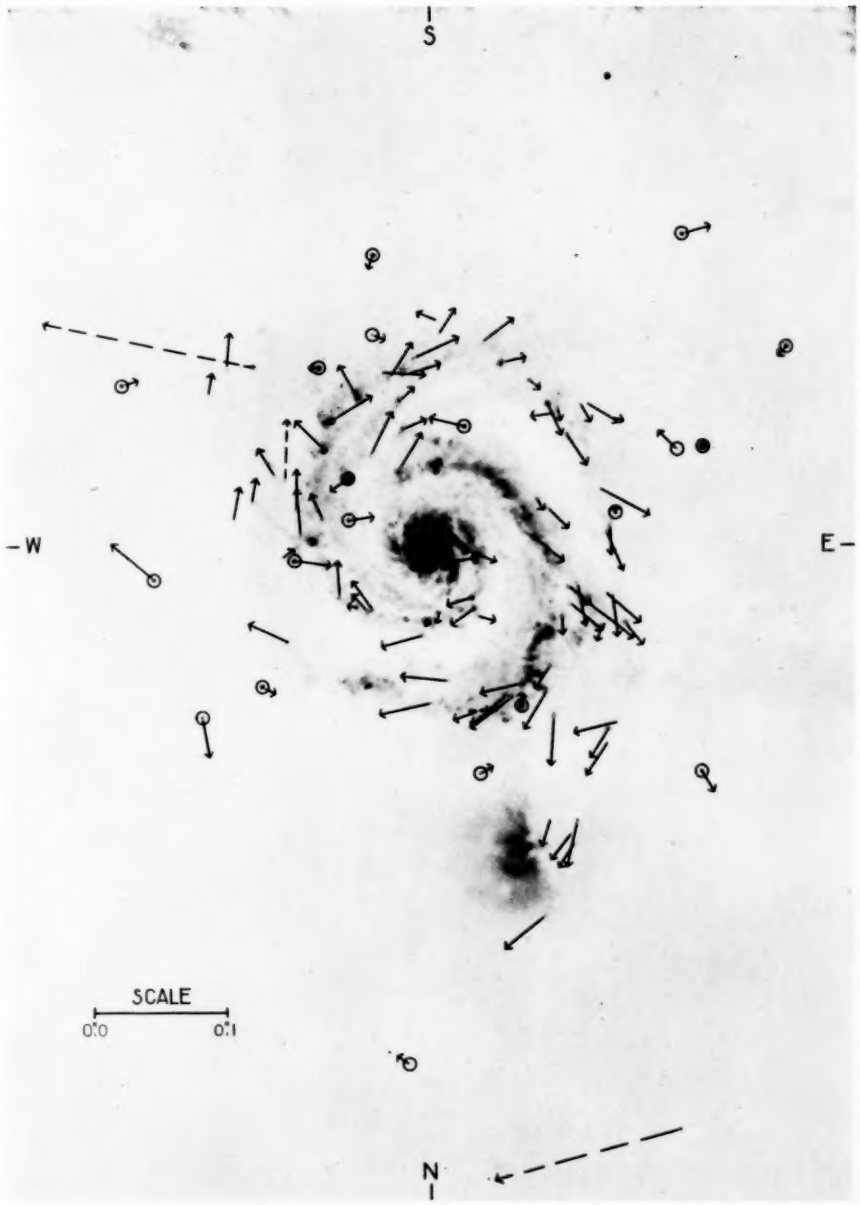
$$\mu_a = +0''.006 \quad \mu_\delta = +0''.001.$$

If now we subtract these quantities from the values of μ_a and μ_δ for the nebular points, we obtain results which represent the internal motions. These are given in the second and third columns of Table II and are plotted in Plate II. The plate also shows the motions of the 23 stars as given in Table I. The 20 comparison stars are surrounded by a circle, while for the stars *f*, *j*, and *r*, which, for the reasons mentioned on page 238, were excluded for comparison purposes, the motions are represented by broken lines. The scale of the motions is indicated in the lower left-hand corner. The arrows represent the motions in about 1100 years.

The plate indicates motions analogous to those found for M 101 and M 33. They may be interpreted either as a rotation combined with a radial motion outward, or as a motion along the streamers outward. Both possibilities are briefly discussed.

a) *Rotational motion.*—In order to discuss the results from the standpoint of rotation, the internal motions of the 79 points (excluding No. 27) were analyzed into components perpendicular to and along the radius. The values are given in the fourth and fifth columns of Table II, the positive sign being used for rotation in the direction ENWS and for outward radial motion. For the rotational component we find 74 positive and 5 negative values; for the radial component 59 positive and 19 negative values, while one is zero. The mean rotational component is $+0''.019$; the mean radial component, $+0''.008$. As the mean distance from the center is $2'.3$, the rotational motion of $0''.019$ annually would indicate a rotation period of about 45,000 years. The radial component is so large, however, that we can hardly believe the motion to be one of rotation only. Similar results have been found in all three cases discussed so far. For M 101 the radial component is 32 per cent of the rotational component; for M 33, 48 per cent; for M 51,

PLATE II



INTERNAL MOTIONS IN MESSIER 51

The arrows indicate the direction and magnitude of the mean annual motions. Their scale (0".1) is indicated on the illustration. The scale of the nebula is 1 mm = 6".2. The comparison stars are inclosed in circles.

TABLE II

ANNUAL INTERNAL MOTIONS

No.	μ_α	μ_δ	Rotational	Radial	Stream	Transverse
1	+0″.022	+0″.009	+0″.007	+0″.022	+0″.011	+0″.019
2	− 27	+ 5	+ 12	− 24	+ 1	− 27
3	− 19	+ 5	+ 18	− 7	+ 16	− 9
4	− 18	+ 13	+ 21	+ 2	+ 21	+ 2
5	− 2	+ 8	+ 3	+ 8	+ 4	+ 7
6	+ 3	+ 2	− 3	+ 2	− 2	+ 3
7	− 31	+ 8	+ 30	+ 12	+ 31	+ 7
8	− 7	− 2	+ 6	+ 4	+ 7	+ 2
9	− 9	− 20	+ 17	+ 14	+ 20	+ 8
10	− 22	− 23	+ 3	+ 31	+ 14	+ 28
11	+ 30	− 19	+ 34	− 4	+ 33	+ 9
12	− 14	− 25	− 1	+ 28	+ 5	+ 28
13	+ 10	− 10	+ 12	+ 8	+ 14	+ 4
14	+ 17	− 8	+ 19	+ 3	+ 19	+ 1
15	+ 17	− 29	+ 27	+ 20	+ 32	+ 10
16	+ 2	− 10	+ 2	+ 10	+ 5	+ 9
17	+ 5	+ 9	+ 10	+ 1	+ 10	− 2
18	+ 16	+ 16	+ 20	+ 11	+ 21	+ 8
19	+ 22	+ 18	+ 20	+ 21	+ 20	+ 21
20	+ 18	+ 15	+ 7	+ 22	+ 21	+ 9
21	+ 37	+ 28	+ 13	+ 44	+ 41	+ 19
22	− 12	+ 16	+ 20	+ 4	+ 20	− 1
23	− 17	+ 27	+ 30	+ 10	+ 31	+ 7
24	− 32	+ 6	+ 30	− 11	+ 26	− 19
25	− 26	+ 22	+ 33	+ 8	+ 34	+ 3
26	− 31	+ 23	+ 38	+ 6	+ 38	0
27	+ 2	− 46				
28	− 13	− 22	+ 14	+ 20	+ 25	+ 3
29	+ 19	− 4	+ 16	+ 10	+ 16	+ 11
30	+ 8	+ 7	+ 10	− 2	+ 11	0
31	+ 6	+ 23	+ 20	− 14	+ 21	− 11
32	− 16	+ 2	− 12	− 11	− 8	− 13
33	+ 15	+ 22	+ 27	− 3	+ 26	+ 5
34	+ 1	+ 22	+ 22	− 2	+ 22	− 4
35	+ 12	+ 29	+ 29	+ 10	+ 31	+ 5
36	+ 13	+ 17	+ 11	+ 18	+ 18	+ 12
37	− 14	+ 21	+ 26	+ 7	+ 25	− 7
38	− 7	+ 33	+ 22	+ 27	+ 33	+ 6
39	− 15	+ 20	+ 20	+ 14	+ 24	− 7
40	− 12	+ 17	+ 18	+ 10	+ 20	− 4
41	− 31	+ 25	+ 38	+ 14	+ 35	− 20
42	+ 14	+ 4	− 10	+ 11	− 9	+ 12
43	− 16	− 22	+ 27	− 5	+ 25	− 10
44	− 11	− 14	+ 17	− 2	+ 17	− 2
45	− 1	− 29	+ 25	− 13	+ 23	− 16
46	+ 10	− 7	+ 6	− 10	+ 3	− 12
47	− 3	− 34	+ 34	+ 5	+ 34	− 3
48	+ 3	− 18	+ 19	+ 1	+ 17	− 8
49	+ 4	− 25	+ 25	− 1	+ 24	− 7
50	0	− 30	+ 29	+ 8	+ 30	− 1
51	+ 2	− 26	+ 21	+ 16	+ 26	0
52	+0″.003	−0″.017	+0″.016	+0″.007	+0″.017	−0″.003

TABLE II—*Continued*

No.	μ_α	μ_δ	Rotational	Radial	Stream	Transverse
53	+0".017	−0".026	+0".024	+0".020	+0".026	+0".018
54	+ 32	+ 2	+ 30	− 10	+ 28	− 13
55	+ 28	− 9	+ 30	+ 5	+ 30	0
56	+ 34	− 15	+ 35	+ 12	+ 37	+ 3
57	− 15	− 6	− 14	+ 7	− 11	+ 12
58	+ 12	− 18	+ 11	+ 19	+ 16	+ 14
59	+ 16	− 34	+ 32	+ 18	+ 34	+ 14
60	+ 5	+ 9	+ 10	+ 1	+ 10	− 1
61	+ 6	+ 33	+ 30	+ 14	+ 32	− 8
62	+ 25	+ 22	+ 9	+ 31	+ 31	+ 9
63	0	+ 14	+ 12	+ 6	+ 14	− 1
64	− 2	+ 38	+ 23	+ 30	+ 32	+ 18
65	− 25	+ 8	+ 26	0	+ 25	+ 2
66	− 37	− 3	+ 36	− 7	+ 37	0
67	− 40	+ 8	+ 40	+ 7	+ 36	+ 18
68	− 30	− 13	+ 29	+ 17	+ 29	+ 16
69	+ 24	− 18	+ 19	+ 24	+ 23	+ 20
70	+ 2	+ 11	+ 9	− 5	+ 10	− 3
71	+ 8	+ 14	+ 16	− 4	+ 16	+ 1
72	+ 23	+ 14	+ 26	+ 7	+ 24	+ 13
73	+ 11	+ 3	+ 10	+ 7	+ 7	+ 10
74	+ 38	+ 20	+ 32	+ 30	+ 25	+ 34
75	+ 26	+ 26	+ 18	+ 32	+ 27	+ 24
76	+ 4	+ 32	+ 30	+ 14	+ 32	+ 6
77	− 2	+ 12	+ 12	+ 3	+ 11	− 6
78	− 33	+ 8	+ 29	− 16	+ 18	− 28
79	− 17	+ 24	+ 29	+ 7	+ 28	− 8
80	−0".006	+0".019	+0".013	+0".015	+0".020	+0".002

42 per cent. It is on the basis of this continuous evidence against a purely rotatory motion that we feel more inclined to believe that the motions are in general along the arms.

b) *Motion along the arms of the spirals.*—Considering the motion as following the arms of the spiral, we find the mean motion to be +0".021, with an additional perpendicular component outward of +0".003. In the case of M 101, we found a small additional motion inward. In M 33 there is a slight indication of motion outward. But in all cases the mean deviations from the direction of the arms are very small. Definite conclusions as to the real meaning of these motions must, however, await further measurements. The best evidence may be expected from several hundred points to be measured in M 33, as soon as another plate can be secured.

Among the stars selected originally for comparison purposes, *f* and *r* require comment. Although their photographic magnitudes cannot be brighter than 16, they show annual proper motions of 0".145 and 0".163, respectively.

I wish to express my thanks to Mrs. Marsh of the computing division, who has performed all the duplicate computations necessary for the derivation of the present results.

MOUNT WILSON OBSERVATORY
June 1921

EXCITATION STAGES IN OPEN ARC-LIGHT SPECTRA

PART II. SILVER, BISMUTH, CADMIUM, ZINC, AIR, AND COPPER[1]

By B. E. MOORE

ABSTRACT

Excitation stages in low-current arc spectra of Ag, Bi, Cd, Zn, and Cu.—By a study of the *variation of the spectrum with current* for from 0.02 to 1 ampere, about *90 lines have been classified* in one or other of the five stages described in Part I. All lines appear first at the negative pole, then at the positive, and later still in the middle of the arc. Lines of Stage I come in first, usually resonance lines, the first terms of principal series. As the current is increased, the arc suddenly flares up and the lines of Stage II appear, the lowest ionization lines, including diffuse subordinate series and terms of the principal series. Lines of higher stages are distinguished chiefly by their inception currents, which are often three times greater for one stage than for the preceding stage; whether they are due to successive ionization is unknown. When lines first come in they are often intermittent and in any case have an appreciable and sometimes a considerable intensity. Before the lines of Stage I appear, the glow shows a continuous spectrum and also bands, probably due to molecules, elementary or compound. In fact most bands require only low excitation, some ceasing with Stage I; but others develop like Stage II lines. *Intensity-current curves for 18 lines* are given. They vary considerably in form, including three different types. Intensity growth *of* the positive pole is similar to that at the negative, as a rule, but later. *The relation* at *these results to the Bohr theory and to the Ritz equations* is briefly discussed. When the ring positions corresponding to the types of spectral lines are represented graphically, it appears that lines of a given stage are associated with rings lying within certain limits and that both these limits are larger in radius the later the stage; but the ranges for the various stages overlap. In a *discussion of Fowler's classes of enhanced lines*, it is pointed out that classification by excitation stages permits a more precise definition of enhancement, since the lines of each stage are evidently enhanced with reference to those of all earlier stages. A *comparison with King's temperature classification* in the case of Cu lines shows no correlation, some of his Class III lines falling in each excitation stage from I to IV.

Arc spectrum of cadmium.—A new resonance line at λ 3779 belonging to Stage I was discovered. Hitherto it had probably been supposed to be an iron line.

Arc spectrum of air.—With low excitation two new lines appear at λ 3064 and λ 3068, which may belong to the positive nitrogen bands.

SILVER

Table I gives a complete list and classification of all lines observed under 1 ampere. Lines of Stage I fulfil the requirements that they develop rapidly at the outset and are easily obtained in the middle of the arc. Stage III lines adhere rigidly to the pole position up to 1 ampere, while Stage II lines are then becoming

[1] The experimental method employed in Part II was the same as in Part I, except that a rotating sector was substituted for the crossed nicol system. This facilitated the readings very much.

long and are decidedly present in the middle of the arc. The line λ 5472 has a later origin than the other d_1 lines. This happens for the same type of line with some other substances.

TABLE I

CURRENT LIMITS IN AMPERES

λ	−Pole	+Pole	Stage
3383*p*	0.035*a*	0.05*a*	I
3281*p*	.035*a*	.05*a*	I
5472d_1	.09	.....	II
5466d_1	.05	.02	II
5209d_1	.05	.02	II
4212d_2	.062	.18	II
4056d_2	.062	.18	II
5090	.....	.7	III
4888	.....	.6	III
4874	.....	.6	III
4669s_2	.2	.6	III
4616	.....	.7	III
4476s_2	.2	.6	III
4396	.....	0.7	III

a, lower current not tried; *p*, *d*, *s*, principal, diffuse, and sharp series, respectively.

BISMUTH

The arc consisted of bismuth in a shallow brass crater at the lower electrode and platinum at the upper electrode. For the weakest currents the arc shows the above-described air features and one bismuth line at λ 4722. This one bismuth line was traceable at the negative pole to 0.015 ampere and was visible at the positive pole to at least as low as 0.035 ampere. The double slope characteristic of the line is shown in Figure 1. A similar characteristic is observed for line λ 5552, although it is later in its origin. The difference between positive and negative pole is a later origin of the lines at the positive pole. Graphically the positive-pole growth of the lines is like the negative-pole growth except that the curves are displaced toward higher currents.

Kayser's table, *Handbuch der Spectroscopie*, **5**, shows a number of bright lines, some of which are marked "enhanced." In this list λλ 5078, 4803, 4798, 4391 (double), and 4308 (double) show intermittently at the positive pole when the current reaches 1 ampere. It does not seem possible, therefore, to place these lines in a class with Stage III, which are quite brilliant but very short

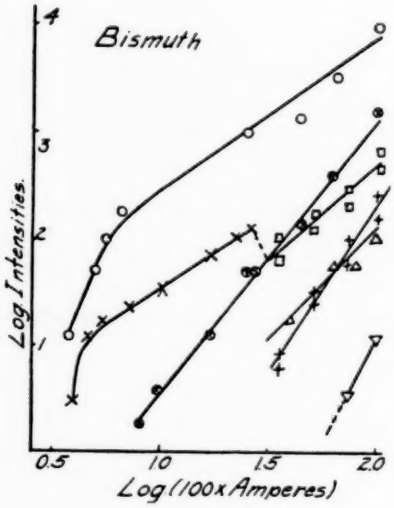


FIG. 1

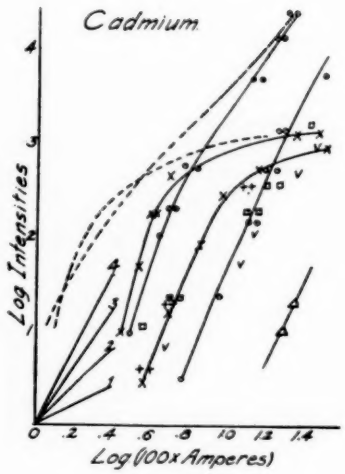


FIG. 2

○ = λ4720, upper −pole
⊕ = λ4720, lower middle
× = λ5552, −pole
□ = λ5552, +pole
+ = λ5552, middle
△ = λ5742, +pole
▽ = λ5742, middle

○ = λ5086, −pole and middle
× = λ5378, −pole and middle
+ = λ6438, −pole
△ = λ6438, middle
□ = λ4800, −pole
V = λ5154, −pole

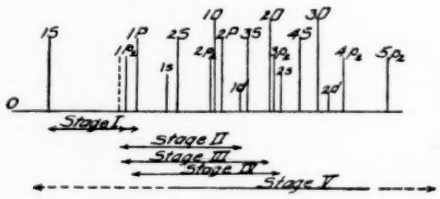


FIG. 3

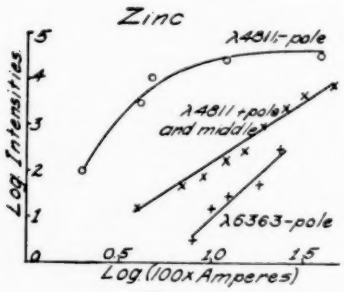


FIG. 4

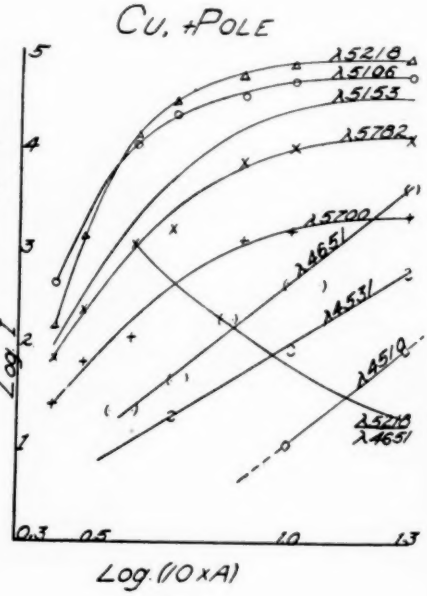


FIG. 5

polar lines at 1 ampere. Lines λλ 4803, 4798, one or both, are present. Kayser does not assign them to the arc and λ 4803 is designated "enhanced." There are two arc lines at λ 4308; one is designated "enhanced." No other enhanced lines or bright arc lines are traceable.

A Stage I line was sought in the ultra-violet at the strong line λ 3067, but the air band interfered precisely. With 0.06 ampere at the negative pole λλ 3596, 3511, and 3397 were present, using the quartz spectrograph, with a five-second exposure, while a three-minute exposure at 0.03 ampere failed to reveal anything but air and λ 4722. These three lines are therefore assignable to Stage II.

Table II shows the lines assembled in stages.

TABLE II

Stage I λ	Stage II λ	Stage III λ	Stage IV λ
4722	5552	5742	4803
	3596	5298	4798
	3511	4122	4308
	3397		

CADMIUM

In the visible spectrum, the ascendancy of λ 5378 both at the pole and in the middle of the arc is readily recognized for very low currents. The development of a few lines is shown in Figure 2. Note the relative position of λλ 5378, 5086, and 6438, Stage I, II, III lines respectively. It might appear that these lines could be extrapolated to a common origin. The difficulty is that the lines suddenly go out at about the positions shown in the graph. The stages are not separated as far as in most substances, but λ 5086 is a decidedly bright line when λ 6438 begins to show intermittently as a faint line. The line λ 5154 has a common origin with λ 6438, although it takes a different slope after its inception.

The real aspirants for Stage I lie in the ultra-violet at λ 3261, Type $1S-1p_2$, and at λ 2289, Type $1S-1P$. The former was easily realized, but along with it came an unknown line, which at first was supposed to be a line given by Morse,[1] found with the Wehnelt

[1] *Astrophysical Journal*, **21**, 223, 1905.

interruptor at λ 3776. A spectrogram, with iron as comparison, with the Rowland grating, showed it to be nearly a duplicate of the iron line λ 3779.4. Hence the natural assumption that this line had been discarded from cadmium as an impurity due to iron. But a spectrogram of iron, at the low currents at which the line may be realized, showed that all lines of iron between the limits of λ 3000 and λ 6000 may be banished from the middle of the arc. As the

TABLE III

λλ	Amperes at		Condensed Spark Intensity	Stage	Type
	− Pole	+ Pole			
5154	0.05	0.19	745	III	$1P-3S$
6438	.04	.16	.....	III	$1P-1D$
4662	.065	.30	.....	III	$1P-2D$
3500	.1*p*	.35	.....	III	$1p_2-1D$
3252	.12	*m*	.....	IV	$1p_2-2S$
4413	.14	.5*a*	.....	IV	.....
4511	.12	.35	.....	IV	.....
6333	.16	.45	.....	IV	$1P-1d$
25	*k*	.....	.....	IV	$1P-4S$
4307	.3	.85	*d*	V	.....
6116	.35	1.	.....	V	$1S-4p_2$
12	*k*	.....	450	V	$1S-4p_3$
6099	.35	1.	.....	V	.....
4614	.....	1.	300	V	.....
5607	.....	.....	.....	V	$1S-5p_1$
04	.....	.....	.....	.....	$1S-5p_2$
5598	.....	.....	300	V	$1S-5p_3$
5298	.....	.....	33	V	.....
5637	.....	.....	11	V	.....
5784	.....	.....	11	V	.....

a, the substance is passing to the molten state.
d, surrounding field disturbs visibility.
k, not separated from the adjacent line.
m, requires five times the exposure of λ 3500 at 0.1 ampere.
p, lower current not studied.

current increases, this new line disappears. This behavior suggests Type $1S-1p_2$ in calcium, strontium, and magnesium. But the line λ 3261 has good claims to represent this type. The line conforms to the requirements of Stage I and for the present must be included in the cadmium list.

Table III gives some observations pertaining to Stages III and IV. In so far as the types of the lines were known, they are also included.

There seems to be some doubt concerning the arc line λ 5378.6. Kayser gives it as an arc line, and λ 5379.6 as a spark line. Steinhausen (see Kayser's tables) gives the latter as an enhanced line. This might imply that there was only one line. Watts's table gives only a spark line. It seems to the writer that there are two lines. Now in the spark λ 5379 is a brilliant companion of λ 5339, which occurs in the spark only. It was thought worth while to investigate these lines and the relations existing in the spark, although it might be said to transcend the scope of studies of the open arc light. Some of the observations upon spark lines are recorded in Table III. They represent well-known arc lines but they were not visible below 1 ampere. The spark produced by the induction coil was giving a spectrum more like the arc spectrum of Kayser's

TABLE IV

λ	Middle Arc		Spark	
	0.14 Ampere	0.25 Ampere	No Capacity	Capacity and Self-Induction
5378.6.....	500	800	0	0
5379.6.....	0	0	3–5	3100
5339.....	0	0	10	2600
5086.....	145	3000	100	1950

tables than the spark spectrum therein recorded. It reduced the intensity of the leading line λ 5086 to one-fourteenth of its value at the negative pole at 0.25 ampere and at the same time brought out subsequent lines of the same series which could not be observed below 1 ampere with the direct-current arc. The principal point which the writer wishes to emphasize is the disappearance of the line λ 5378 in the spark. This is shown in Table IV, which is a composite of observations of arc and spark upon four lines, or upon three lines if there be someone to insist that the first two are only one line. If there are two lines, λ 5378 is extinguished upon passing to the spark. If there be but one line, it suffers a practical extinction upon passing to the spark with no capacity and then a renewal by adding self-induction. This seems less plausible than the two-line assumption.

Table V shows the lines assembled in stages. Stage VI represents a departure in that spark lines are assigned to it. How late these lines occur in the development is not known.

TABLE V

Stage I λ	Stage II λ	Stage III λ	Stage IV λ	Stage IV λ	Stage V λ	Stage VI λ
5378	5086	5154	3252	6116	5784	5379
3779	4800	6438	6333	112	5637	5339
3261	4678	4662	6325	099	5298	Many
	3611	3500	4511	5607	4614	others
	3466		4413	604		
	3299			598		

ZINC

The resonance line λ 3076, Type $1S-1p_2$, was the first line investigated. No really satisfactory results were obtained, as the air lines are just in the way. What was called λ 3076 was a line which grew more rapidly than the adjacent lines. The line of Stage II at λ 4811 on graph and leading line of the principal series of triplets behaves at the negative pole exactly like a line of Stage I. At the positive pole it has the characteristics of a line of Stage II. The *d* triplet in the ultra-violet also belongs to Stage II. The current steps make Stages II and III necessary.

Figure 4 shows the development of λ 4811, Stage II, Type $1s-mp$, and of λ 6563, Stage III, Type $1D-mS$. There is a rich list of lines in Stage III; generally there is a rich Stage II list.

The lines are assembled in Table VI according to stages.

TABLE VI

Stage I λ	Stage II λ	Stage II λ	Stage III λ	Stage IV λ
3076	4811	3345	6563*a*	
	4722	3303	(3072)*b*	4924
	4680	3282	3036*b*	4912
			3018	

Lines λλ 4924 and 4912 are true spark lines. They are brighter in the spark spectrum with the small inductor than the triplets of Stage II. Stage IV only represents here the next stage as

observed. The lines are doubtless of the same origin as Stage VI in cadmium, Table V. In the spark λ 4811 receives the same setback as λ 5086 in cadmium.

AIR AND ITS COMPOUNDS

The spectra of air are more or less disturbing with all substances, as has already been noted in Part I. The purpose is now to specify the air spectra more definitely. These spectra show best with copper electrodes, and they are most easily followed in the glow arc.[1] As shown in Part I, there is first a low continuous spectrum in the middle of the arc and at the poles. There are two well-defined lines at λλ 3064, 3068, which have not been traced to any definite metal, and which, on account of their persistence, are assigned to air. They should be looked for in gas free from oxygen and nitrogen. These lines are overlapped by a fluting system and do not seem to be connected with the doublet, but may be connected with a fluting system which has a distinct head at λ 3805. If this is true the whole fluting system is probably connected with the second positive nitrogen spectrum. Certainly the latter is easily identified in the visible spectrum and is present at both electrodes just outside and never inside the polar illumination. It therefore has a low excitation. The oxides of the metals have very rich and strong spectra. For the metals these spectra rigidly pertain to radiation coming from the surfaces of the electrode. (Magnesium and aluminum are exceptions.) When the poles become definitely established upon passing from the glow to the true arc,[1] these oxide spectra disappear from the part of the electrode adjacent to the polar illumination, but they still persist outside of this limit. Hence it is apparent that the new ionization products at the instant of the pole "flare" are formed at the expense of the oxides. These ionization products which are first produced in the "flare" certainly represent the first well-defined ionization lines. They occur at low current and the potential required for the excitation is not high.[2] The flutings, therefore, correspond to a lower excitation.

[1] Simon and Malcomb, *Physikalische Zeitschrift*, **8**, 471, 1908.

[2] Ionization potential of cadmium 8.92 volts. Tate and Foote, *Bulletin of the Bureau of Standards*, **14**, 485.

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Since the principal series doublet lines λλ 3274, 3247 may be photographed outside the visible limits of the arc and at very low currents, and since the ratio of intensity at pole to middle differs but little from unity, these lines may be taken as typical lines of Stage I. Three other lines have been placed in this stage: λλ 5106, 5782, and 5700. It did not appear that they could be placed in Stage II, but the analysis may be at fault. Consider the five upper lines in Figure 5. This figure represents a study of the positive pole with an arc operated upon a 750-volt circuit. For a one-centimeter arc the current will go out between 0.25 ampere and 0.3 ampere. When attempting to operate upon a higher potential the arc shifts from the glow to the true arc form and makes quantitative readings practically impossible. From this curve one can readily see that λ 5106 may exist after λ 5218 has disappeared. But one could not approximate the course of λ 5782 and λ 5700 from the figure. Hence it was necessary to get some evidence from the glow discharge and from the flare when the glow goes over into the true arc form. In the glow, line λ 5106 is still very distinct in the absence of the "*d*" doublet λλ 5218, 5153. Some of the time λ 5106 was seen to the exclusion of λ 5782 and much of the time to the exclusion of λ 5700. But the latter lines are inherently weaker than λ 5106. Generally they were traceable, too, when the "*d*" doublet was absent. But more importance was attached to the behavior when the "flare" occurred. It has been repeatedly suggested that this flare indicates the appearance of an essentially ionization stage. Now in this flare there is an outburst of the doublet, λλ 5218, 5153 and its companion doublet λλ 4063, 4023. There can be no mistakes in assigning these two doublets to Stage II. Then if there is an error in the other three green lines it probably lies in the assignment of the pair of λλ 5782, 5700 to Stage I, instead of Stage II. The type of this pair of lines is unknown. Line λ 5782 has the Zeeman pattern[1] corresponding to the shorter wave in the "*d*" doublet and λ 5700 the same pattern as the longer wave of the doublet. Such a pair of lines in Stage I is certainly unprecedented.

[1] Runge and Paschen, *Astrophysical Journal*, **16**, 131, 1902.

Line λ 4631 is a representative of the sharp series (see Fig. 5). At an intensity of about ten or a little greater, λ 4651 and λ 4531 have the habit of becoming very intermittent. They seem to insist upon shining distinctly or not at all. When these lines are in that intermittent state the "*d*" doublets are brilliant and extending far toward the middle of the arc. Hence it appeared that these two lines could not be traced to the same limits as λ 5218. They are accordingly placed in Stage III. The position of λ 4510 (see Fig. 5) is typical of the eleven lines in Stage IV.

The photographic density of λ 4651 was taken by King as a standard of reference.[1] It is strictly a short line for small currents.

TABLE VII

Stage I		Stage II		Stage III		Stage IV	
λ	King	λ	King	λ	King	λ	King
3247	II	5218	II	4531	III	5732	.....
3274	II	5153	II	4481	III	5646	III
5106	II	4063	II	4651	III	5408	.....
5783	III	4023	III			5392	.....
5700	III					5360	.....
						5355	.....
						5293	.....
						5017	.....
						4705	III
						4587	II
						4510	II

Hence for short lengths of arc King's exposure may be regarded as exposures on the pole. Furthermore, it appears that the intensity of the line grows very uniformly with the current. But when the density of this line is chosen as a unit of reference, the line λ 5218 should at first increase and then later decrease over threefold before 2 amperes is reached. This is shown in Figure 5 by the curve of the ratio λ 5218 divided by λ 4651. In general, King's method of study is adequate when there is a progressive change in the rate of development of the lines. It ought to succeed very well with such cases as are given in Table IV under cadmium, particularly in the ultra-violet.

[1] *Astrophysical Journal*, **20**, 21, 1904.

The lines are assembled in stages in Table VII. There were a number of other lines observed between 1 and 2 amperes but observations were very indefinite. King's Groups II and III behave differently under self-induction. They are shown in Table VII and are distributed indiscriminately through the successive stages of excitation.

DISCUSSION

The discussion will be taken up under the following topics: "Preliminary Statement," "Thermionic Processes," "Resonance and Ionization," "Spectral Types," "Lowest Excitations," "Excitations of Molecules and Compounds," "The Second Stage in Excitation," "Subsequent Stages in Excitation," "Line Limits," "The Spark Discharge and Excitation Limits," "The Rate at Which Lines Develop," "Enhancement in the Arc and Spark Discharge," "Solar Enhancement."

Preliminary statement.—The basis of this discussion is a few well-established facts in gaseous conduction and in the emission of electricity from hot bodies. There is need to mention two simple equations:

$$(1)\ \tfrac{1}{2}mv^2 = eV \quad \text{and} \quad (2)\ eV = h\nu.$$

Equation 1 asserts the equivalence of the kinetic energy of an impact and the electrical energization, i.e., excitation, arising therefrom. Equation 2 states that the potential V, in an electrical energization, is directly proportional to the frequency of a luminous vibration, when the energy of electrical excitation disappears as radiation. Equation 1 represents an excitation and equation 2 represents a recovery after excitation has ceased. If one recognizes these two conditions as parts of a reversible process it should lead to no confusion if the radiation is spoken of as an excitation.

Thermionic processes.—The emission of electricity from hot bodies has had an extensive investigation in the last score of years.[1] It is natural to designate these processes as thermionic. This

[1] *The Emission of Electricity from Hot Bodies*, by O. W. Richardson, F.R.S., published by Longmans, Green & Co., gives a most lucid treatment of the subject and contains a very complete reference list to the literature.

implies a mechanical process, for the kinetic nature of heat is always taken for granted. Some subtleties have arisen concerning the nature of excitation during the process of chemical action. In so far as the present paper is concerned it need only be stated that chemical changes are accompanied by thermal changes; and any thermal loss by radiation may be accompanied by either line, band, or continuous spectrum radiation. Simon[1] and his students have developed the thermionic conception of the arc very carefully and have been able to explain a great many features in both the direct- and in the alternate-current arc. The arc must produce enough energy at the electrodes both to free the surface electrons and material from the adjacent matter and to impart a motion to the electrons and ions. After this condition is attained the electrons and ions are subjected to an accelerating force or fall of potential across the arc. Since the fall is practically constant there is a uniform equality between the accelerating force and the retarding force of the medium. Just off the electrode surface the electrons are subjected to the accelerating force of the *medium fall* and at the same time are in motion due to a velocity arising from repulsion from the electrodes. This action and the radiation from the adjacent electrode surface produce greater heat in the immediate neighborhood of the electrode than in the middle of the arc. This in turn permits greater freedom of motion, greater acceleration, and greater velocity of electrons and ions. This results in greater excitation and a richer spectrum in the pole illumination just off the electrode surface than is found in the middle of the arc.

Resonance and ionization.—Numerous recent experiments upon the emission of electrons from hot bodies have shown that there are two stages in the electrical excitations at low potentials.[2] The potential for the latter is considerably larger than for the former stage. When the spectral emission is examined it is found that the lower excitations correspond to the fundamental line of some

[1] *Physikalische Zeitschrift*, **8**, 471, 1907. Also his references and subsequent contributions in the same journal.

[2] A grasp of the resonance and ionization concepts may be obtained from the following contributions: Tate, *Physical Review*, **7**, 686, 1916; *ibid.*, **10**, 81, 1917; Tate and Foote, *Bureau of Standards*, **14**, 479, 1918. For magnitudes of resonance and ionization potentials, see Foote and Mohler, *Philosophical Magazine*, **37**, 46, 1919.

definite series of lines, while the latter corresponds to the last line or limit of the series. Hypothetically the theory has been advanced that the ionization releases the whole series of lines and all related series. Evidently from equation 2 all these lines cannot be represented by eV. In fact, none of the lines could be represented by this product except the final line of the series, which has never been observed.

Spectral types.—The Bohr[1] treatment of spectral series is very easy to visualize, although it does not afford as accurate a formula for the determination of the spectral lines as the theory of Ritz.[2] According to the Bohr theory the sequence arises because there exists a sequence of ring positions about a central ionic nucleus in which an electron may vibrate and be in a state of unstable equilibrium. The return of an electron from an outer to an inner ring produces radiation. The electron may then be free to return to another more stable ring position nearer the nucleus and emit another radiation. Each radiation represents a potential fall according to formula 2. When the electron has returned to its stable condition the sum of all the potential "falls" is equal to the ionization potential. If the return to the stable condition may take place in an entirely promiscuous fashion, it is possible to realize a very rich spectrum from an ionization. Bohr pointed out, in his first contribution upon this subject,[3] that the outer extension of the ring system would be interfered with by the material in the gaseous medium. He computed the number of rings, or the equivalent number of spectral lines which could be realized in the Balmer series for hydrogen at different pressures. To realize more lines one needed to have a more attenuated gas and greater volume excitation for increased intensity. In any finite medium an electron cannot expend all the energy of its excitation upon a single return. It must impart a portion of its energy to the surrounding medium, and the returns to the stable ring positions will be mostly

[1] *Philosophical Magazine*, **26**, 1, 1913.

[2] *Annalen der Physik*, **12**, 264, 1903. In the Ritz theory the lines may be expressed by $f(m, A, a)$, $f(n, B, b)$ (see types throughout the experiments), where m and n represent a sequence of numbers and each value of m and n determine a term. The function signs, f, a, and b are usually suppressed for brevity in notation.

[3] *Ibid.*, **12**, 9, 1903.

made up of returns from rings nearest the stable position. Hence the first lines of the series are invariably the strongest. It ought to be possible, therefore, to realize more lines of a series from the emission of hot bodies in a vacuum than from an arc operating at atmospheric pressure. To this point we shall later return.

Low and high excitations.—High excitations belong with high velocity electrons, like those required to produce the X-rays. The term may be used relatively. It is known that an excitation lower than resonance may be secured. The fall from one ring position to another represents a loss of potential energy and has an excitation equivalent. One may designate these conditions and the accompanying spectral lines *ad libitum*, as produced by lower and higher velocities, lower and higher currents, lower and higher potentials, or lower and higher excitations, according to which of these features one wishes to emphasize.

Lowest excitations.—From the progressive appearance of the first spectral lines in the polar illumination, then in the middle of the arc, and then upon the outer mantle of the arc to the exclusion of other lines; then from the great displacement of these lines when the magnet acts upon the arc; and lastly from the analogy of these lines to proven resonance lines, it is concluded that these lines appear at the very lowest potential which will excite spectral lines. If there has been no error in the observations, *all lines in Stage I represent the lowest line excitation.*

Excitations of molecules and compounds.—It is now proper to state that when the current is reduced to the last limit of line excitation there is still present a weak continuous spectrum, narrow bands are often decidedly conspicuous, and fluting spectra at the poles are often observed. If one considers the total radiation, these features are more important than the initial lines. Clearly the energy expended in the lines is only a small portion of the total radiation; and, indeed, the line radiation would be an entirely insignificant portion if all the energy which goes into heat were considered. From the discussion of the preceding topic it appears that these radiations must all be classed as low excitations.

The second stage in excitation.—As the current increases new lines appear in the polar illumination. Sometimes this increase

in current occurs in a discontinuous manner; the sudden outburst or "flare" in the illumination arises. In this "flare" there is a new list of lines. Such an outburst in the current points either to a first or to another ionization of the electrode material. When these experiments were nearing completion the writer checked up Stage II lines with the appearance of lines which came out in the "flare." In every case of "flare," Stage II lines and the "flare" lines were identical. Consequently with some degree of confidence one may designate Stage II lines as the beginning of ionization in the arc. Before a "flare" takes place there is often observed a series of flutings coming from the face of the electrodes. This is particularly noticeable with copper. Just as soon as the "flare" occurs, the flutings cease at the electrode base adjoining the "flare." When a carefully cleaned copper surface is used as an electrode, the discharge is very migratory until some oxidation ensues. The flutings come from this product. When the "flare" ensues, flutings no longer come from the adjacent electrode base; but if the arc is stopped it will be found that this very electrode base is the portion most thickly covered with the oxide. It was clear that the oxide was forming previous to the "flare," and one may safely say that the flutings resulted from this combination. Thermionically considered, such a chemical process takes place with loss of heat which has partly disappeared as radiation, and which according to equation 2 is accompanied by a readjustment of the electrons. It is also apparent that these flutings belong with the low excitations which precede the "flare." In the "flare" stage the electrons emitted from the electrode base arise to a potential value greater than that represented in the fluting combination, and there is now a profuse outpouring of electrons from this identical oxide. It would appear that this process would either stop the formation of the oxide at the base of the "flare" or reverse the process and decompose it. The latter effect certainly does not take place. The amount of oxide has at least remained as large as it was before the "flare" and it seemed that it had quite possibly increased. In the latter case is it possible for the oxygen ions from the air to combine with the copper without producing the flutings? It becomes not only a subtlety of chemical action but also of ionization energy which is

not answered here. The compounds of the chloride salts in Part I in a few cases were found not to withstand an excitation as great as that required for Stage II lines. They broke up in the polar illumination and recombined in the middle of the arc where the excitation was lower. Hence the spectrum of these products also belongs to the lowest excitation. On the other hand, accepting the molecular identification of certain band lines by other spectroscopists as correct, it appeared that some radiations which belonged to the molecules of the elements did not diminish in the polar illumination but that they progressed in their development very similarly to other lines and, more particularly, similarly to the development of Stage II lines. This makes it clear that the elements in molecular combination represent a stronger energy bond than the chloride compounds.

Subsequent stages in the excitation of lines.—As just shown, lines of Stage II originate in an ionization. The question arises whether the subsequent stages have their origin in farther ionizations. That would be the easiest but not the only possible explanation. There is no "flare" accompanying them as in the case of lines of Stage II. The electrical examination of high-potential arcs has not been carried to the low currents of the third-stage lines, and in some cases not as far as the fourth-stage lines. It was this fact which led to the investigation by Mr. V. L. Chrisler in the following contribution.[1] There is another reason which may be assigned for the appearance of these subsequent stages in the arc. Under the topic "Thermionic Processes" the change in the degree of freedom in motion with temperature has been noted. Under "Spectral Types" the restriction of the outer rings has been mentioned. As the current in the arc increases there is an increase in temperature, and, by reason of the expansion, a greater degree of freedom between the molecules, and greater possibility of acceleration between the molecules, and a greater impact energy in the moving electrons. Increasing the current, then, would bring about ultimately another ionization if such an ionization is possible. But before reaching such a stage, the excess in potential over that required to produce the earlier ionization goes into other forms of energy, and principally or entirely heat energy. Now this heated

[1] Page 273 of this number.

or expanded medium will make it possible to realize a greater number of the external electronic rings (see the discussion upon "Spectral Types") about the ionic nucleus. Since it is these ring positions which determine the lines, the lines may be used to define them, and the current which causes the inception of the lines may be used to determine the stage at which these lines begin. Now the spectral types and the corresponding ring positions about the nucleus may be represented graphically by using the sequence values of the terms as computed from the Ritz equation. This method is followed for some of the lines in cadmium in Figure 3. The position of the nucleus is shown at "*O*" in this figure. The cologarithms of the values of the terms are then plotted from this point as origin. The positions of the lines then represent tangents to the rings whose centers are at "*O*." (The meaning of the letters is given with the types in the text.) The arrows represent the stages and ring limits for the lines in the stage. Stage V represents lines obtained in the spark. It is therefore not a continuity with the previous arc stages. If the restraint of the medium determines the outer ring limit it might seem that there should be a stage to mark each successive outer ring limit. It is doubtful if the measurements are capable of adequate refinement to test this possibility. But as one looks at the figure and notes the slight outward extension of the rings between Stage III and Stage IV, the existence of intermediate stages seems rather improbable. In fact the inquiry would be rather, "How is it possible to distinguish such slight difference in ring limits as that represented between Stage III and Stage IV?" The answer is in the current value required to cause an inception of the stage. In passing from Stage II to Stage III and thence to Stage IV the inception current is nearly trebled in each case. The stage limits seemed to be determined by a group of related rings rather than by each successive ring. The infra-red and ultra-violet possibilities in the ring system did not come under observation, and this interferes somewhat with the realization of some possible stages, if they are defined in terms of ring limits.

Line limits.—The outermost ring which can be realized for a given current is designated the "excitation limit" for that current.

According to the Bohr ring theory (see discussion of "Spectral Types") the return of an electron from an outer to the innermost ring position may take place in any number of accidental steps. Such a condition would make all steps equally probable, and therefore all possible lines equally probable. This is not strictly the case. Some types of lines, whose rings are intermediate, practically fail. It seems as if there is a possibility that the return of an electron to an intermediate position is not entirely a matter of chance but that there are conditions which predetermine the stopping place of the electron before it starts upon its journey from one ring to another. This question has been kept constantly in mind during the experiments. The effort was made to see if there was any evidence of definite selection in the formation of lines in the different stages. Nothing very conclusive was observed; but there was a *little* evidence bearing upon the question, as will be seen from the following analysis.

As the current increases, the new stage lines begin in the core of the polar illumination. The earlier lines are pushed outward and toward the middle of the arc. Now one may examine the old lines in a position which collimates with the new ones or in the outer mantle just outside of the position of the new lines. It is then seen that the old lines are increasing at a relatively slow rate in the central position but at a comparatively rapid rate outside. This is particularly true with reference to the growth of Stage I lines. The new slope for these lines when the new lines appear is shown in the figures. Now those figures represent the central growth, and it is apparent that when new stages begin part of the earlier radiations go to the radiation in the new stages. Now if the intensity determinations were accurate enough to justify the process, one could reduce the intensity in the collimating position by the intensity in the outer mantle and leave an intensity equal to that which arises from the excitation of these lines in the core of the illumination. This rather hazardous process would in some cases leave an unimportant development for some of the earlier stage lines in the core where the later stages are appearing. Reversals show that one is not warranted in completely removing the earlier stage lines from the core excitation. Now the inner core is

a position of high temperature and highest ionic velocities. If we assume that Maxwell's law of distribution holds, the average velocity will be increasing with the current, and the lower velocities will be progressively less important. There will be an "effective" velocity in the direction in which the current flows. The slow-moving ions will have the same amount of "effective" energy as the rapid-moving electrons. Now a moving electron might come into the range of an ion that had a velocity which represents a kinetic energy equivalent to a fall from some inner ring position to the stable position. In this condition the electron might not be able to return to a ring position inside of the one which represents the kinetic energy of the ion with which it combines. Furthermore, if an electron may make an incomplete return, it may be driven off again (re-ionized) from the recovered position. If this may be true, then also the ion may be subjected to a force sufficient to prevent a complete return. Goldstein was able to suppress the series lines of the alkalies and to bring out other groups of lines alone by passing a high potential discharge through a constricted space. There was here a relatively large density of electrons and low density of atoms. The conditions are somewhat similar within the small space of the core illumination, where also the number of ions which could have a low velocity might be very insignificant. Hence it might be that there is a "restraint" in the ionic system which determines the degree of the recovery of an electron. If one designates the outer limit of line production in the series of lines as the "excitation limit," it might be possible to designate the inner ring to which the electron returns as the "restraining limit." An "excitation limit" and a "restraining limit" would fix definitely the limits of radiation before the radiation ensues. The evidence for the former limit in the pressure exerted by the medium is fairly definite. The attempts to follow the latter have been rather illusive. The Sommerfeld[1] quantum theory of spectral radiation is expressed in terms of two limiting conditions, which are called the azimuthal and radial quantum conditions respectively. Lines

[1] W. Kossel and A. Sommerfeld, *Berichte der Deutschen Physikalischen Gesellschaft*, **21**, 240, 1919.

are produced by a diminution of the radial term by any number of quantum units and by a change in the azimuthal value by $-1, 0,$ or 1 units. As the writer interprets this paper, the physical conditions which determine the azimuthal term is the state of ionization. If one were to apply this to Stages II, III, IV of these experiments it would seem that the arrow files for those stages in Figure 3 ought in all cases to extend to the term p_2, wherein it would appear that ionization takes place from particles which are first thrown into a stage of resonance, and that they return to the limits of the resonance stage before recovery from ionization. An ionization from the p ring is accompanied by a loss of two electrons for bivalent atoms, as is shown by two methods of analysis. The series beginning with the ring position $1S$ are supposed to be due to the loss of one electron. The difficulty here is that $1S-1p_2$ and $1S-1P$ represent resonance, and the subsequent members of the same series represented by $1S-mp_2$ and $1S-mP$ are ionization lines. Two ionization potentials have not been observed for these substances. One can escape the dilemma by supposing that there is only one ionization, the one which carries off two electons for bivalent atoms, and that the recovery takes place by single electrons. The first recovery would take place from exterior rings to the azimuthal position p_2, and the second to the position $1S$. It will require much further analysis to see whether the above-suggested "restraining limits" can be best expressed in terms of the degree of ionization present at the time the radiation ensues.[1]

The spark discharge and excitation limits.—The presumption is usually made that the spark discharge first ruptures the gaseous medium, producing thereby the air spectrum; and second, that this discharge is followed by a discharge of ions and electrons from the electrodes along the rarified, highly heated path.[2] Herein the displacements occur at a higher velocity than in the arc and also in a rarified medium. Further, the spark discharge is both alternating and intermittent. Hence, if there were forces built up within

[1] J. Stark and students have zealously maintained that successive ionizations are present in spectra. For literature see *Annalen der Physik*, **64**, 376, 1921.

[2] A. Schuster and G. Hemsalech, *Philosophical Transactions* (A), **139**, 189, 1899.

the atom by the electric action to produce the foregoing internal restraining limits they would not be sustained in the spark except for the very briefest interval of time.

The rarified medium would permit of wider limits for the outer rings, and as a result there would be a larger possibility of lines. When, in the restricted conditions of the arc, a great amount of energy is going into one type of radiation, upon passing into the spark, the energy in the expanded, higher excited medium may pass to the other types or farther outlying rings in the same type of lines. This action is shown conclusively by the intensities in the composite table, Table VIII. The first two lines in each substance are the first and fifth lines of a definite series type, and the remaining two lines are found only in the spark discharge.

TABLE VIII

λ	Cadmium		λ	Zinc	
	0.25 Ampere Arc	Spark		0.25 Ampere Arc	Spark
5086*b*	270000*a*	1950	4810*b*	25000	2800
5604*c*	0	300	5310*c*	15	450
5339*d*	0	2600	4912*d*	0	3300

a, extrapolated from 0.22 amperes; *b*, Type $1p_1-1s$; *c*, $1s-5p_3$; *d*, leading spark lines.

The leading series line λ 5086 in the spark of cadmium is only one-fourteenth as bright as the same line at 0.25 ampere in the negative polar illumination of the arc. The fifth member, line *c*, Table VIII, of the same series was not observed in cadmium, and was only just beginning in zinc, where it had but one-sixteen-hundredth of the intensity of its leading member. In the spark each of these two lines has an intensity nearly equal to one-sixth of their respective leading lines. It would require an extended investigation to show how much of this change has been brought about by each of the factors, expansion of the medium and velocity of impact.

The rate at which lines develop in intensity.—Lines have a minimum value at which they first become visible. This current is called their inception value. After their inception, lines progressively increase in intensity in very different ways. In Figure 2 the

straight lines 1, 2, 3, 4 represent developments proportional to the first, second, third, and fourth power respectively of the current. The curves, for a few lines, might be characterized as having two rates of development, with a progressive change through a short range from one rate to another. These lines are generally limited to Stage I. The leading line of the zinc triplets seems to be an important exception. There are a number of lines which show nearly a uniform growth in intensity after their inception. Many lines develop most rapidly just after their inception. In the graphs the total current is plotted against intensity. It might appear that the effective current is the amount added to the current after the inception of the lines. If this were true, the abscissae in the graphs should have been represented by $\log (i-i_0)$ instead of by $\log i$, where i is the observed current and i_0 the inception current. Two broken lines in Figure 2 were plotted, using $\log (i-i_0)$ as abscissae. The curves to which they are tangent are the original curves. If all curves were plotted upon this plan there would be greater variation shown than when plotted against total current as abscissae. Some of the lines would even begin slowly and then for greater currents increase more rapidly. In the visible spectrum, the effect upon the eye is that of a sudden beginning of the lines, the variation consisting of an intermittent radiation. For this reason the graphs with logarithms of total current are given greater credence.

Enhancement in the arc and spark discharge.—The term "enhancement" covers the relative increase of a line or lines with respect to another line or lines when the conditions under which the lines are produced change.

Fowler[1] distinguishes three classes of enhancement, viz., (1) enhanced lines like the H and K lines of calcium, which are well developed in the ordinary arc; (2) lines which only appear with small intensities in the arc, such as the enhanced lines of iron; (3) lines which do not appear in the ordinary arc (except very locally at the poles) but are strongly developed under spark conditions—as in the well-known magnesium line at λ 4481.

[1] Fowler, *Phil. Trans.* 214, 259, 1914.

Fowler designates the p, s, and d lines of the bivalent elements herein discussed as enhanced. He includes also the narrow doublets of the same type, which certainly did not come out below Stage V. He lists also the f type and combination lines of the narrow doublets, all of which arise at excitation beyond the limits of present experiments. Fowler states that these lines are enhanced with respect to a few types of lines which he selects from the arc list of lines, and designates these as arc lines. These are the D and S singlets and the d and s triplets. It is not clear how many lines of these four series are used for comparison. From the observations here discussed, it appears that $1S-1p_2$, the first member of the s series, comes in Stage I while the next member is decidedly of the ionization type; it appears in Stage II or later and is therefore enhanced with respect to the earlier stage. In Stage I there are never more than a few lines and often only one, or a doublet pair of lines. They are always the *first* members of some definite type of series and never the *whole* series. The latter members of the series to which the Stage I lines belong show enhancement just as distinctly as members of other series. Particular attention was directed to this feature in barium, where the Stage I line λ 5536 was separated from the leading member of the p series with difficulty. The type of this line is $1S-1P$. The next member of the series is found at λ 3072. There are troublesome air bands in this region when the small quartz spectrograph is used. But if this line belonged to the class of lines which are not enhanced according to Fowler, one ought to have realized it with the Rowland grating for weak currents. In fact it was not as easily realized either at the pole or in the middle of the arc as the p_1 doublet pair. Evidently it is not "vibrating system," i.e., type, which determines enhancement. If one compares the later stages with Stage I, and if one accepts the reasonable conclusion that Stage I corresponds closely to a resonance condition, the conclusion would be that enhancement arises from an ionization. Mr. Megh Nad Saha[1] makes the statement, "Modern theories of atomic structure and radiation leave little doubt that the 'enhanced lines' are due to the ionized atom of the element." He then proceeds to compare H and K, two ionization lines, with g, the resonance line

[1] *Philosophical Magazine*, Oct. 1920.

of calcium. This freedom would sweep almost the complete spectrum of substances into the enhanced class. Different ionizations, i.e., the removal of a different number of electrons from the atom, have been evoked to explain enhancement. That the removal of more than one electron is necessary to explain the p and d series for bivalent elements was shown first by Lorenser.[1] He found the universal constant, N, in the Ritz equation, four times too small. This change is brought about in the Bohr equation by changing from the univalent condition, e^2, to the bivalent condition $(2e)^2$, where e is the charge of an electron. Now the determination of ionization potentials does not decide how many electrons are emitted; but more than one ionization potential would clearly point to different ionizations unless the potential values are multiples. This has not been realized.[2] To say that one electron and then the other is removed at one and the same ionization potential is purely a gratuitous assumption. The possiblity of successive ionizations in the arc as a cause of lines appearing in stages, was pointed out to Mr. V. L. Chrisler by the writer, and Mr. Chrisler proceeded to study the very low-current arcs particularly in reference to this point. In the following paper Mr. Chrisler shows that stages in ionization have *not* been realized within the limits of these experiments. Hence enhancement as a result of ionization is an incomplete explanation.[3]

Fowler does not define his Class (2) lines definitely enough for comparison. As the current increases, a rich list of Stage II lines appear.[4] One cannot prophecy how far the comparison of the weaker later lines with the second-stage lines can be carried. But the point which should be emphasized here is that such a comparison would be of one ionization line with another, and of lines enhanced, as some of the foregoing writers have indicated, due to ionization. Upon the basis of inception stages,

[1] Reference by Kossel and Sommerfeld, *Berichte der Deutchsen Physikalischen Gesellschaft*, **21**, 252, 1919. These authors show the bivalency of the p series from the term difference $2p_2 - 2p_1$.

[2] Tate and Foote, *loc. cit.*, and many subsequent experiments.

[3] See the closing remarks upon "line limits," p. 265.

[4] October 1921. Many iron lines of Fowler's Class (2) appear in Stage II.

all later stages are, of course, enhanced with reference to earlier stages. But stages may or may not be due to successive ionizations. So far as the writer can see Fowler's Classes (1) and (2) are representatives of one kind of enhancement. Fowler's Class (3) represents lines either nearly or completely absent in the arc. These lines are generally attributed to high velocity, high potential excitations, which ionize an inner ring of electrons. In this class are Fowler's magnesium lines λ 4481, *p* narrow doublet, and possibly the whole *p* narrow doublet series as well. The writer has seen only the member λ 4481 in the spark. It had the same dominance in the spark spectrum of magnesium that the cadmium lines λ 5579 and λ 5539, and the zinc lines λλ 4924, 4912 have in the spark spectrum of these elements. (See Table VIII, and pp. 264–266 and reasons there given for considering both expansion and higher excitation to be active causes of the enhancement.)

Solar enhancement.—One may consider an excitation to arise (1) from low-velocity impacts of the magnitude which is usually seen in the arc; (2) from the high velocity impacts which appear in the spark and vacuum discharges and which correspond to removal of internal electrons; (3) from a thermionic ionization. There can be no doubt about (1), and very little doubt about the analysis of (3). That there are high velocity electrons in solar disturbances is made evident by Hale's experiments upon the Zeeman effect in solar vortices. One would confidently expect high velocities and intense ionizations wherever they may occur, to bring out such lines as cadmium λλ 5579, 5539, zinc λλ 4924, 4912, and magnesium λ 4481. The conspicuous enhancements in the sun are not these high ionization lines, but the prominent lines of the Stage II group which appear at the earliest ionization.

Let us take the most conspicuous solar enhancement, known as the calcium pair λλ 3968, 3933, *p* series leading lines, which are enhanced with respect to the line λ 4227, *S* series leading line, as one advances to higher levels in the solar atmosphere. Now λ 4227 is the resonance line of calcium, and the change in the arc with increasing current conforms to the conception of an ionization arising at the expense of the neutral atomic excitation. As one passes to the solar conditions, one must recognize that the thermal

rather than the electrical action causes the thermionic process. Recently Mr. Megh Nad Saha[1] has made some very excellent and opportune computations upon the degree of dissociation of calcium, strontium, and barium for different pressures and temperatures, and has applied the results to hypothetical temperatures and pressures for different levels in the chromosphere. The treatment substantially follows the method of Eggert,[2] who discusses thermionic dissociation in fixed stars. The postulate is made of a reaction of the form

$$R \leftrightharpoons R_+ + e - U$$

where e is the electron and U the energy change. A resonance radiation is concerned with a radical R, or with its atoms, while ionizations are concerned with nuclear types R_+, R_{++}. Ionization potentials do not determine the valency of these nuclear types, but there is spectroscopic evidence to show that valency does enter into the radiation, and furthermore it is generally conceded that the radiation accompanies return from a nuclear type to an antecedent type. Now let us note again the Eggert-Saha theory. By dissociation we arrive at a condition which obliterates R and leaves R_+ in the attenuated solar atmosphere. In this process the inner ring, $1S$, is wiped out and along with it all lines which converge to this limit. The dissociation was computed from the potential which gives complete ionization, and this is a condition which would obliterate all lines. To get the radiation of the p series it is necessary to allow the electrons to return to the $1s$ ring, which becomes a new "restraining limit" for the electrons; a position, which, according to Sommerfeld, will represent a new azimuthal velocity but with a zero radial velocity. The process could be better understood if someone could make it clear how it is possible to have the fixed ionization potential and still to leave the electron in a ring position which is removed only one step from the normal ring, and in this position be ready to receive ionization impacts from moving electrons. There are some other things which will need examination. If the ring $1S$ is wiped out, so also are all lines of the series. The

[1] *Philosophical Magazine*, July, Oct., and Nov. 1920; Feb. 1921.

[2] *Physikalische Zeitschrift*, **20**, 570, 1919.

first line appears in Stage I but the subsequent lines appear with ionization. If complete dissociation can remove entirely this ring, then the subsequent lines ought to be realized along with the first line, but in the arc the subsequent lines are realized in Stage II. In the solar chromosphere most of these lines would be unfavorably located because of the ultra-violet absorption of our atmosphere. But the second line of the series for barium might be investigated. It lies at λ 3072. In sodium the leading term of the *p* series is the resonating type. According to the dissociation theory the whole series should vanish in the solar chromosphere. If subsequent lines of the series are ionization lines one might expect to find λ 3303 in the chromosphere[1] just as it is realized in Stage II.

BRACE LABORATORY
UNIVERSITY OF NEBRASKA
May 1921

[1] Observations by S. A. Mitchell in 1905 begin just to the red of this position. Mr. Mitchell informs the writer that the plates used in the flash spectrum of the 1905 eclipse were weak in the ultra-violet region λ 3303. See *Astrophysical Journal*, **38**, 407, 1913.

THE LOW-CURRENT ARC

PART I. THE ARC IN AIR AT ATMOSPHERIC PRESSURE

By V. L. CHRISLER

ABSTRACT

Low-current arc in air.—Potential-current curves up to 0.5 ampere were obtained *for electrodes of various materials* (C, Ag, Cd, Cu, Fe, Sn, Zn, and salts of Ba, Ca, Cs, Na, and Sr); also the *cathode and anode falls and the gradients in the center* were measured with the help of probing platinum wires. As the current is increased the glow form of the arc changes suddenly to the true-arc form and at the same time the cathode fall drops sharply, in the cases of Ag, Cu, and Fe changing from 214 to 28 volts, from 290 to 16 volts, and from 205 to 24 volts respectively. Ag, Cu, Fe, and Pt all gave the glow discharge up to 0.1 ampere. The true-arc form probably begins with the volatilization of the electrode material and the ionization of the vapor. The gradient in the center of the arc is proportional to the length of the arc, decreases with increasing current, and varies in step with the ionization potential of the metal vapor from the electrode.

Extensive investigations have been made of the arc, and the theory of its action has been much discussed. Mrs. Ayrton[1] has shown that the relation between the current i flowing through the arc and the potential-difference v across the arc can be expressed by the equation

$$v=\alpha+\frac{\beta}{i}+\left(\gamma+\frac{\delta}{i}\right)^2,$$

where α, β, γ, δ, are constants.

Child[2] has made a study of the arc at different gas pressures, determining the anode and cathode fall and the potential gradient through the arc. He also pointed out that a hot anode is not necessary for an arc discharge, but it is essential that the cathode be hot if the arc is maintained.

J. Stark[3] found that at constant pressure, the potential fall, across the arc, for a given current, decreases when the density of the gaseous medium increases. This he showed was due to the conservation of heat by the heavier gases, an accompanying

[1] *The Electric Arc.*

[2] *Physical Review*, **19**, 117, 1904.

[3] *Annalen der Physik*, **18**, 213, 1905.

rise in temperature, and a greater free path for the electron movement. He also found that the anode fall depended upon the material and the density of the medium adjacent to the electrode. He found, further, that cooling the electrode raised the potential.

The thermionic conception of electrode and gaseous action has been a subject of extensive and elaborate investigation.[1] H. Simon[2] has applied this conception to the action of the arc. He states that, due to the electrodes being hot, they are emitting electrons. At the cathode this is in the direction of the current and therefore lowers the cathode fall, but at the anode it is against the current and increases the anode fall. He also considers that the ionization in the arc increases with increasing current, but not in proportion to the current, as the volume of the arc also increases and thus limits the ionization. His students have made extended studies confirming his theory.

Simon's students[3] carried the study of the arc to low currents for some electrode materials. For 0.5 ampere and less, they found that there was a negative crater formed, but no positive crater. They also found when the discharge passed from the glow to the arc form, that the character of the discharge at the anode remained the same until a greater current strength was reached. Simon states for these small currents that the evaporation from the negative crater does not suffice to fill the whole arc with electrode gas, and that the discharge from the arc light is partly carried by the surrounding gas. For larger currents with metallic electrodes he concludes that the discharge is very largely carried by the metallic vapor or gases, and that this metallic vapor has a vanishingly small resistance.

The spectroscopic experiments by B. E. Moore[4] reveal very important changes at low currents where the observations of the previous experimenters were far from complete. It was therefore

[1] Richardson, *The Emission of Electricity from Hot Bodies.*

[2] *Physikalische Zeitschrift*, **8**, 471, 1907, and subsequent contributions in the same journal.

[3] Malcolm, *Physikalische Zeitschrift*, **8**, 471, 1907; Grotrain, *Annalen der Physik*, **47**, 141, 1915.

[4] *Astrophysical Journal*, **54**, 191 and 246, 1921.

desirable to redetermine some of these low values. Since there was not a continuity of the spectroscopic changes, it appeared possible that some discontinuities in the electric action had been overlooked. Furthermore, the observations of Simon's students did not cover all of the substances which Moore had studied, or many others which Moore has not investigated. A priori, one has no right to say that an untried substance will act like other substances. Besides, even when the form of the equation, for different substances, is the same, the constants of the equation have individual values.

Spectroscopically there is a difference between the portion of the arc near the pole and that at the center, a difference between the central core and the surrounding mantle. These all need to be viewed in the light of the electrical behavior of the arc. Lastly, electrical action may be of special significance in the "pole effect" or the shift of spectral lines at the poles.

In these experiments it is necessary to call attention to the following features of the electrode fall. The potential at the electrodes possesses two components, viz., (1) a part of the energy is used to heat the electrodes, (2) another part is used to impart velocity to the ions. The electrodes will lose heat both by conduction and by evaporation in case vapors are given off. As the electrodes heat, less energy will be required for heating purposes and more will be available to impart velocity to the electrons and ions. Ultimately one reaches a point by increasing the current where the discharge surface is heated sufficiently to produce self-ionization. The energy required in this process might be called a "latent heat" of ionization.[1] In this condition only enough drop at the electrodes is necessary to sustain the action. For increased current the ionization surface thereafter broadens.

METHOD OF MEASUREMENT

As a source of potential three 1000-volt generators were used which could be operated in series or in parallel, depending upon the potential and current desired. The total potential across the arc was measured with a Weston voltmeter, and the current

[1] The gas laws apply to ionization processes, Richardson, *op. cit.*

through the arc with a Weston ammeter. The cathode and anode falls were measured with a Thompson electrometer. The cathode and anode falls were taken as the difference in potential between the electrode and a fine platinum wire inserted in the arc as close to the electrode as possible. The platinum wire was coated almost to the tip with cement.

RESULTS AND DISCUSSION

It was found very difficult to obtain accurate measurements for the anode and cathode falls, as the small point of light from which most of the discharge passed was continuously changing its position, and the values obtained for the anode and cathode falls were very much greater when the platinum wire was outside this point of light. It was often necessary to wait a considerable time for this point of light to become stationary long enough, where the probe wire was placed, to obtain a reading of the electrometer. These values were taken as the anode and cathode falls. In a few cases it was impossible to obtain any reading, as the point of light was shifting so rapidly that the electrometer needle did not come near enough to rest to give any approximate indication of the potential to be determined.

Electrodes of copper, silver, zinc, cadmium, iron, and tin, as well as carbon with salts of sodium, calcium, strontium, barium, and caesium have been used. The usual type of curve showing variation of potential fall across the arc, with the current flowing, was obtained, Figure 1 being that for copper. These results are similar to those of Simon, Malcomb, and others (*op. cit.*). With copper in particular, the discharge apparently takes place under two conditions, one of which has been designated by Simon and others as the glow current, and the other as the arc. From the curves it will be noticed that the glow form requires nearly 300 volts more potential than is required in the arc form for the same current. The discharge is very unstable through this region, as it tends to change constantly from one form to the other. The glow current was obtained with other metals, but not to such a marked degree as when copper electrodes were used.

An attempt was made to apply the Ayrton equation to the potential-current curves for low currents, but without much

success. For an arc of 1 cm length this equation reduces to the form

$$e=\frac{a}{i}+b$$

where a and b are constants. It was found that this equation fitted the curves very well in all cases where the current was over 0.5 ampere and for some electrode materials for currents as low as 0.25 ampere. For smaller currents, the curve deviates decidedly from that of the hyperbola which the Ayrton equation gives. An attempt was made to represent the data by an empirical equation,

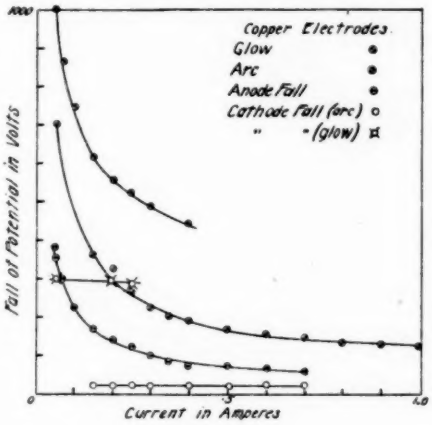

FIG. 1

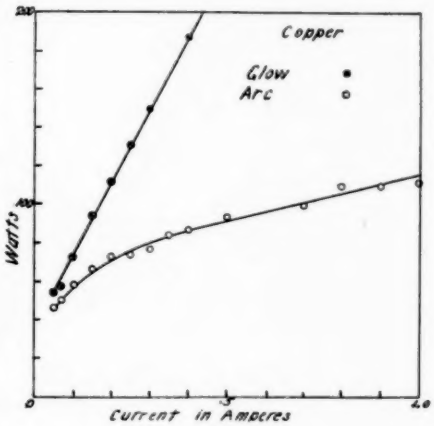

FIG. 2

but no equation containing a few constants seemed to express the conditions adequately.

The total energy was also plotted. Figure 2 shows the results for copper, and from these curves it is evident that the energy consumed in the glow current is much greater than that consumed in the arc for the same current. For larger currents the curve approaches a straight line, as required by the Ayrton equation. For smaller currents, however, the curves deviate decidedly from straight lines for all of the metals tested when the discharge was in the arc form. For the results obtained with the other metals which were tested see Figure 3. The results obtained with salts on carbon are shown in Figure 4.

After obtaining these curves, the anode and cathode falls were determined by the method previously mentioned. For the smaller currents there was only a point of light at the electrodes, and the anode or cathode fall was measured when the wire was inside this point of light or "polar illumination." For larger currents

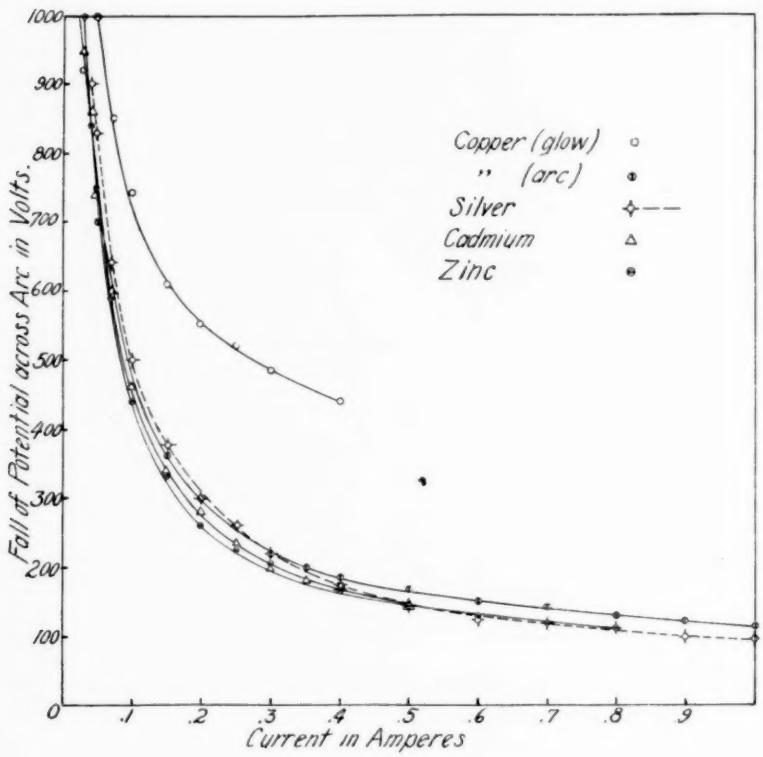

FIG. 3

this polar illumination increases in size and gradually extends across the arc.

In the glow current the point of light at the cathode disappears and in its place is found a diffuse glow. Just beyond the latter is a Crooke's dark space. In this case the cathode fall was found to be much higher. Table II gives the cathode fall for copper, iron, and silver.

The anode fall is the same for either form of discharge. From the curves of Figure 1 it will be seen that the change in the cathode fall for copper electrodes accounts approximately for the increased voltage required for the glow current.

For the arc discharge the cathode fall is almost independent of the current strength. With some electrode materials it increases slightly for smaller currents.[1] The anode fall is not constant and always increases for smaller currents and at about the same rate as the total potential. Figures 5 and 6 show curves of the anode and cathode falls for the various materials tested as electrodes.

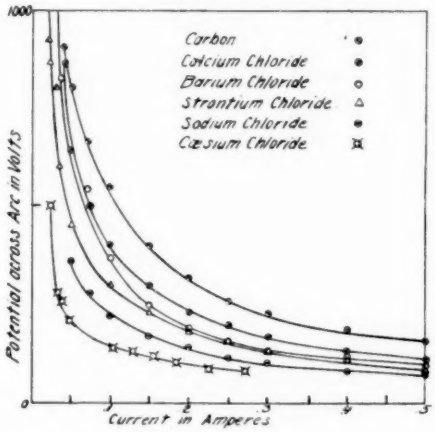

FIG. 4

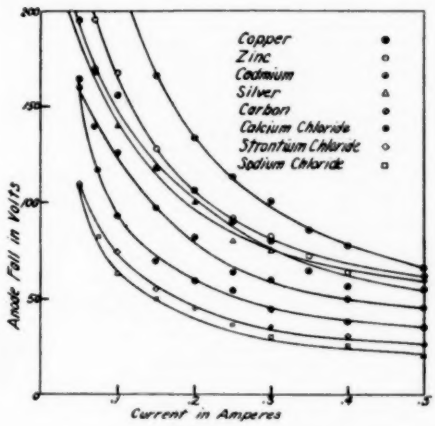

FIG. 5

The general form of the curves are the same as Grotrain found for the materials which he tested.

A few measurements were also made of the potential fall along the center of the arc. This potential fall was found to be directly proportional to the length of the arc, which agrees with the results obtained by Grotrain and Child. This potential fall through the center of the arc decreases at first very rapidly with increasing current. Stark states that an increase in the density of the gas in the arc decreases the fall of potential due to the conservation of heat by the heavier gases, and an accompanying rise in temperature, hence a greater free path for the electron movement. If

[1] Grotrain, *op. cit.*

this statement is accepted, the amount of metallic vapor in the arc, for very small currents, must increase quite rapidly as the current increases to account for the decreased fall in potential. Another factor which probably affects this potential fall is the ease with which this metallic vapor is ionized. If the potential-current curves across the center of the arc are plotted for these different metals and salts, it is found that the curves do not coincide, but fall one below the other (see Fig. 7). For elements of which the ionization potentials have been determined, the writer finds that

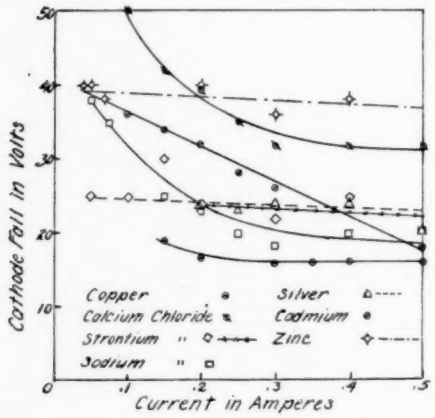

FIG. 6

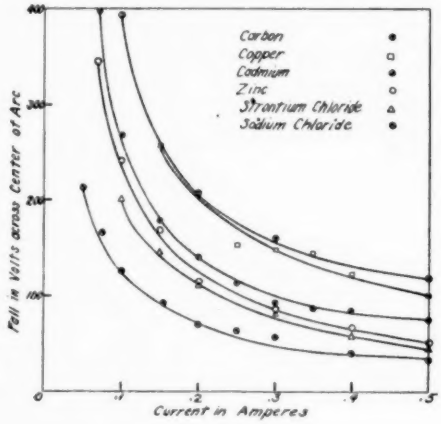

FIG. 7

in general the relative position of the curves is the same as the ionization potentials, in so far as these ionization values are known.

Energy-current curves were also plotted for the center of the arc. The results are shown in Figure 8. Simon, Malcolm, and others state that the glow-current discharge is carried by air, and that its characteristics are the same for all electrode materials. The total potential fall across the center of the arc when it is in the glow form is the same for silver and copper electrodes, but the anode and cathode falls are both smaller when silver electrodes are used. The cathode fall for silver is 75 volts smaller than for copper electrodes. This shows that the energy consumed in the center of the glow arc is greater for silver than for copper electrodes. From this it is quite evident that the air is not an exclusive carrier for the glow discharge when copper and silver electrodes are used. At

the present time this behavior has been investigated carefully for only two substances, copper and silver, but it is hoped to carry the investigation to other electrode materials.

As would be expected, the energy-current curves for the glow arc have a different slope from that for the true-arc form, but according to Simon there should be but one slope for the glow, whereas, as above noted, there has been one observed for copper and another for silver. Whether there are one or more slopes here, it can be seen that the curve for each substance in the true-arc form must intersect the glow curve. Above the point of intersection the true arc is stable, and below the intersection the glow is the more stable form. Provisionally, the term "latent heat" has been used. Just as water may be carried below the freezing-point, so the true arc, upon diminishing the current, may be carried into the region of the glow discharge. The point of intersection of these curves conforms very closely to the beginning of lines of Stage II as found by Moore. The slope in the true-arc form, then, is due to the ease with which the vapor passes from the electrode into the arc and also to the ease with which it is ionized. The vapors conserve the heat, and make possible a greater free path. At a given current, also, the distances of the curves above the x axis have a degree of parallelism to the ionization potentials (see Table I). Zinc appears out of order in this arrangement, but the zinc oxidizes badly when the arc is burning in air, with the result that the arc is full of vapor of zinc oxide which would undoubtedly lower the potential fall in the arc.

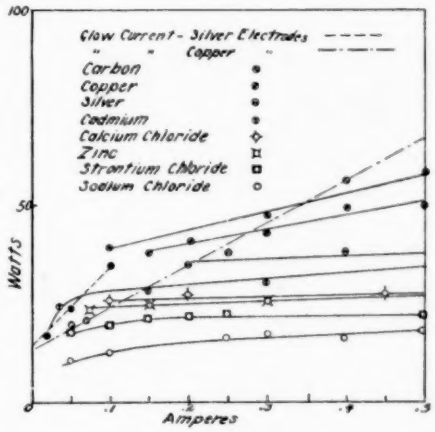

FIG. 8

One of the most interesting questions that has arisen in the study of the arc is, What are the conditions that cause the glow

discharge instead of the arc? Simon states that the glow discharge depends upon the oxides of the metal present and upon the melting-point. From the present investigation it is quite evident that the glow current is independent of the melting-point, as a glow current was easily obtained with tin and lead which have low melting-points but high boiling-points. A glow current was not easily obtained with zinc and cadmium. Zinc and cadmium

TABLE I

Electrodes	Watts	Ionization Potential
Carbon	44	.....
Copper	41	.....
Silver	35	.....
Cadmium	30	9.0
Calcium	26	6.01
Zinc	25	9.3
Strontium	22	5.67
Sodium	16	5.13

have low boiling-points as well as low melting-points. Copper, iron, silver, and platinum were also tested as electrodes and all gave the glow-current discharge up to one-tenth of an ampere. One of the most important features observed was the discontinuity in the cathode fall when the discharge changes from the glow to the true-arc form or vice versa. This has been observed for all cases of change in the form of discharge. Table II shows the discontinuity in the cathode fall for three substances, copper, iron, and silver. For copper electrodes the cathode fall in the glow is eighteen times as large as in the arc discharge.

TABLE II

Electrodes	Cathode Fall in Volts	
	Arc Form	Glow Form
Copper	16	290
Iron	24	205
Silver	28	214

The energy consumed at the cathode was much greater in case of the glow current, due to the increased cathode fall (see Table II),

but the discharge was spread over considerable area, so it is probable that the surface temperature was lower than it was at the point on the negative pole to which the discharge passed when it took the arc form. From the metals tested it would seem that the glow current appeared when the cathode was not heated sufficiently to cause the metals to be volatilized readily, or possibly sprayed out into the arc. Richardson speaks of the electrons being evaporated from a hot surface and of their having a latent heat of evaporation. From these observations it would appear that the temperature at which the electrons evaporate readily into the arc must be closely connected with the boiling-point of the metal. After the discharge passes to the arc form it is generally considered that the temperature at the point of discharge remains about constant; that is, an increase in current simply increases the area of discharge and the greater evaporation keeps the temperature constant. This effect of evaporation was especially noticed with silver electrodes. The surfaces were polished before using, and after using a very short time even with small currents the cathode had small pits 0.5 mm deep; small globules of silver also appeared on the surface. After the surface became pitted in this manner it was very difficult to get a glow current, as the discharge would seize on one of the small points and remain in the arc form. As soon as the surface of the electrodes became oxidized it was also more difficult to get a glow discharge. This latter action agrees with the results found by Simon.

When the discharge passed from the glow to the arc form there was a sudden increase of the current, indicating that there must have been a large increase in the number of electrons which were leaving the negative pole. This points clearly to an ionization of the electrode material. If there were a previous ionization and evaporation of the electrodes, then this is the second stage in the process. Spectroscopically, Moore finds this discontinuity accompanied by an outburst of lines of Stage II (see previous contribution). The works of Tate, of Tate and Foote, and of Foote and Mohler[1] indicate that the earlier spectrum lines are due to the resonance, and not to the ionization. It would seem justifiable, therefore, to

[1] Bureau of Standards, *Scientific Papers*, Nos. 400 and 403; Tate and Foote, *Philosophical Magazine*, **36**, 64, 1918.

regard this discontinuity in the pole fall as the true beginning of ionization of the electrode material.

A few potential measurements were also made in the outer mantle of the arc. It was found when the discharge was in the arc form, for very small currents, that for points outside the polar illumination near the cathode the potential drop between them and the cathode was almost as large as the cathode drop for the glow-current discharge. As the current was increased, this drop decreased, but was still large compared to the potential drop between the cathode and the point inside the polar illumination. At this outer surface Moore found the fluting spectrum to continue in the arc form of discharge, and in the outer mantle adjacent to the pole discharge he found the nitrogen excitations. This would indicate that in the outer mantle of the arc there was practically none of the electrode material which was ionized. It must also be a region of small ionic velocity compared to the center or core of the arc.

Successive ionizations have been postulated to explain spectral lines of different types, and very high ionizations to explain X-ray emissions. The first inference one would naturally make in reference to the sequence of lines found by Moore is that there existed a sequence of ionizations.[1] It has been found that only one ionization makes itself conspicuous in the arc at very low currents. In fact, the current is so low in some cases that it was impossible to realize its beginning point. This is particularly true for the alkalies. Successive ionizations might be of less importance than the first. They would, therefore, manifest themselves in a less pronounced way; but it seemed, if such ionizations were present, that they should become manifest in a change in the slope of the energy curve. No inflection has been found, however, although careful attention was given to this possibility. It is therefore not safe to conclude that ionizations subsequent to the initial flare are present within the range of these experiments.

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University of Nebraska
May 1921

[1] Stark and students, *op. cit.*

THE SPECTRUM OF RADIUM EMANATION

By R. E. NYSWANDER, S. C. LIND, and R. B. MOORE

ABSTRACT

Spectrum of RaEm, λλ 3982 to 7450.—Two capillary discharge tubes were filled with 0.2 and 1 curie of carefully purified emanation, respectively, and both visual and photographic *measurements* were made with a 4-prism spectrometer. The relative intensities of the lines differed markedly, as a rule, from the previous observations of Watson and Royds and Rutherford; many strong lines of the 120 previously measured were not found and yet of the 44 lines obtained, 9 are *new lines*. *Changes of intensity with duration of the discharge* were noticed, some lines decreasing, some increasing in strength, while the color of the discharge changed from a bright glow to violet. λ 5483 and some other *lines flashed out on reversing the current* after a thirty-minute run and then quickly disappeared.

Occlusion of RaEm in discharge tube.—After a discharge had passed through the glass capillary tube containing 0.2 curie for 5 hours, 35 per cent of the emanation had been occluded, most of it in the platinum mirror surrounding the cathode. The other tube became quite hard after a four-hour run.

Modification of Duane's apparatus for purifying RaEm.—The copper wire used to remove oxygen and hydrogen is spirally wound on a silica tube and is heated indirectly by an electrically heated Pt wire passing through the tube, instead of directly by a current through the Cu wire. This arrangement requires less current and less attention.

The spectrum of radium emanation has been determined by Ramsay and Collie;[1] Cameron and Ramsay;[2] Rutherford and Royds;[3] Royds,[4] and Watson.[5] The observations of Ramsay and Collie were entirely visual and showed a bright spectrum which rapidly disappeared and was replaced by the secondary spectrum of hydrogen. The first photographs of the emanation spectrum were those of Cameron and Ramsay, whose results showed a strong resemblance to xenon;[6] hydrogen also made its appearance in the spectrum. Rutherford and Royds photographed the emanation lines with a single (glass) prism spectrograph, using the emanation from 130 mg of radium. Hydrogen lines were also observed, but to separate these from the emanation lines a side tube attached to the spectrum tube was immersed in liquid air, and at the point of condensation of the emanation its lines disappeared, leaving

[1] *Proceedings of the Royal Society*, A, **73**, 470, 1904.

[2] *Ibid.*, **81**, 210, 1908.

[3] *Philosophical Magazine* (6), **16**, 313, 1908.

[4] *Ibid.*, **17**, 202, 1909.

[5] *Proceedings of the Royal Society*, A, **83**, 50, 1910.

[6] *Ibid.*, A, **82**, 22, 1909.

those due to hydrogen. Royds repeated the work, using a concave grating of a dispersive power, of 16.8 A per millimeter, and was able to photograph about thirty-five of the more intense lines already obtained by Rutherford and Royds with good agreement and extended the observations farther into the ultra-violet. Watson's investigation was undertaken with a view of accounting for the discrepancies between former observations and his own results; he employed both a prism spectrograph and a grating. His results are in very good agreement with those of Rutherford and Royds.

For the photographic work of the present experiments a Browning spectrometer with a train of four prisms and photographic attachment was employed, at the University of Denver. The results extended from λ 3982 to λ 7449, being limited in the violet end of the spectrum by the opacity of the glass system. The spectrum of helium was used as a comparison standard. To avoid relative displacement of the two spectra on the plate, a lens was fixed in front of the collimator slit, and the images of the two sources were focused alternately on the slit. By means of a small shutter, adjoining portions of the slit could be illuminated separately. The wave-lengths of the emanation lines were computed by the aid of Hartmann's dispersion formula. The dispersion of the instrument is 13 A per millimeter at λ 4000, and 136 A at λ 7000. The total length of the spectrum between these limits is about 6.8 cm. All measurements of wave-lengths were made with a Gaertner comparator of 200 mm range fitted with a screw of 1 mm pitch. Individual measurements of a line as read on the comparator seldom differed by as much as 0.005 mm, which will give an estimate of the accuracy of the results. The wave-lengths recorded in the table were determined from six photographs, and where a line appeared on more than one plate the mean value is recorded. The more intense lines were found on each of the six photographs. Two types of dry plates were employed, the Standard Orthonon and the Wratten Panchromatic. In addition to the spectrograph, a Hilger constant-deviation spectrometer was arranged so that visual observations could be made simultaneously with the photographic.

The method of purification of the emanation was developed by Lind and is a modification of Duane's apparatus. In addition to the process of purification as described in the note,[1] the emanation was frozen down in liquid air for removal of the residual gases by pumping. After purification the gas was collected in small glass vacuum tubes of capillary bore with platinum electrodes sealed in very small bulbs at the ends. Before the liquid air was removed from the vacuum tube in which the emanation was condensed, the tube was sealed off and the photographic exposure was then started as soon as the tube could be adjusted in front of the slit of the spectrograph. The photographs were obtained almost entirely from two spectrum tubes. The first of these contained 208 millicuries of emanation. Two exposures of two and three hours duration respectively were secured from this tube. It was then broken into small pieces along its length and each piece measured for occluded emanation. The total occlusion in the tube was 35.1 per cent, this being the largest amount of occluded gas measured in any case. This occluded emanation was found to be confined largely to the platinum mirror surrounding the negative electrode. The color of the tube changed from the characteristic bright glow at the beginning of the exposure to a violet color after about one hour's excitation. The second vacuum tube contained approximately 1000 millicuries of radium emanation. Four photographs were secured from this tube with almost continuous excitation for nearly four hours, when the tube became quite hard. After the conclusion of our photographic work with this tube, unfortunately it cracked, leaving us without exact measurements of both occlusion and total quantity of emanation. Small, fused, silica, electrodeless, vacuum tubes of capillary size were also tried. They were excited inductively by means of copper coverings deposited electrolytically on platinum coatings on the ends of the tubes. No effect on the photographic plate could be detected after more than one hour's exposure with these tubes.

It was not possible to photograph the entire spectrum on the plate at one exposure. Accordingly the plates were adjusted to receive the violet and red ends of the spectrum alternately. The greater portion of the spectrum appeared on each plate, leaving

[1] See note at the end of this article.

TABLE I

Photographic Plate	Wave-length	Int.	Watson	Int.	Royds	Int.	Rutherford and Royds	Int.
4	7449.5	1						
4	7269.6	1						
2, 4, 6	7054.0	3	7057	3				
			6749	0				
			6627	0				
			6605	0				
2, 4	6562.2†	1						
			6361	1				
			6309	5				
			6270	0				
			6224	2				
			6204	0				
			6079.3	0			6079*	0
			5977.4	3			5976*	1
			5944.9	2			5945*	1
4	5894.4	4						
4	5888.6	6						
			5838.8	0			5829*	1
			5765.2	1			5765*	1
			5716.1	6			5715.0	1
			5683.0	0				
			5608.4	0				
			5582.60	8			5582.2	8
			5546.6	0				
	5483*							
			5394.4	3				
							5392.4	0
			5386.3	2				
			5371.5	2			5372*	0
			5363.0	2				
			5255.0	1			5257*	1
			5238.0	0				
			5194.9	0				
			5119.5	3			5120*	2
			5084.66	10	5084.45	1	5084.5	4
	5058*							
							5060*	2
			5045.0	4				
			5038.3	1				
			4991.7	0				
			4978.87	10	4979.02	3	4979.0	4
							4965.6	0
			4958.0	2				
			4950.2	4			4949.4	00
			4915.7	4			4914.6	00
			4891.3	4			4889.5	0
2, 4, 5	4860.9†	1			4861.55	10	4861.3	
			4856.4	4				
	4826*		4829.4	4	4828.46	1	4827.8	1
			4817.78	7	4817.33	5	4817.2	4
			4797.3	2	4796.73	1	4796.7	1
			4793.2	2				

* Visual observations.

† H 6563.0, 4861.5.

TABLE I—*Continued*

Photographic Plate	Wave-length	Int.	Watson	Int.	Royds	Int.	Rutherford and Royds	Int.
	.....	.....	4785.8	0	.....	.....	.....	.....
	.....	.....	4768.77	7	4768.16	5	4767.9	3
	.....	.....	4752.4	1	.....	.....	.....	.....
	4735*	.....	4732.2	1	.....	.....	.....	.....
1, 2, 3, 4, 5, 6..	4721.2	3	4721.8	5	4721.70	2	4721.5	5
	.....	.....	4702.33	5	4701.88	3	4701.7	2
4, 5.....	4680.9	1	4681.01	9	4680.92	10	4681.1	10
	.....	.....	.....	.....	4671.58	1	4671.8	1
	.....	.....	4658.8	0	.....	.....	4659.3	1
4, 5.....	4644.0	2	4644.36	9	4644.29	15	4644.7	10
	.....	.....	.....	.....	4634.13†	3	.....	.....
2.....	4631.4	1	.....	.....	4631.89	2	.....	.....
	.....	.....	.....	.....	4628.08	1	.....	.....
2, 4, 5.....	4625.3	2	4625.66	10	4625.58	15	4625.9	8
2.....	4617.8	1	.....	.....	.....	.....	.....	.....
1, 2, 3, 4, 5, 6..	4609.2	9	4609.70	7	4609.40	10	4609.9	7
5.....	4603.7	1	4604.58	9	4604.46	6	4604.7	4
	.....	.....	4586.2	1	.....	.....	.....	.....
	.....	.....	.....	.....	4580.03†	3	.....	.....
1, 2, 3, 4, 5, 6..	4577.6	8	4578.0	8	4577.77	8	4578.7	7
2.....	4572.5	1	.....	.....	4572.66	0	.....	.....
2.....	4567.4	1	.....	.....	4568.24	2	.....	.....
	.....	.....	4547.0	4	.....	.....	4549.9	1
	.....	.....	4527.87	2	.....	.....	.....	.....
	.....	.....	4513.4	1	.....	.....	.....	.....
1.....	4510.2	2	.....	.....	.....	.....	.....	.....
1, 2, 3, 4, 5, 6..	4508.5	8	4508.00	6	4508.68	7	4509.0	9
	.....	.....	4503.52	3	4503.89	2	4504.0	2
6.....	4497.8	1	.....	.....	.....	.....	.....	.....
1.....	4492.7	1	.....	.....	.....	.....	.....	.....
1, 6.....	4489.8	1	.....	.....	.....	.....	.....	.....
1.....	4487.8	1	.....	.....	.....	.....	.....	.....
1.....	4485.2	1	.....	.....	.....	.....	.....	.....
1.....	4482.4	1	.....	.....	.....	.....	.....	.....
1.....	4473.6	1	.....	.....	.....	.....	.....	.....
1.....	4470.8	1	.....	.....	.....	.....	.....	.....
1.....	4467.1	1	.....	.....	.....	.....	.....	.....
1.....	4463.3	1	.....	.....	.....	.....	.....	.....
1, 2, 3, 4, 5, 6..	4459.4	7	4459.3	7	.....	.....	4460.0	10
	.....	.....	4439.6	3	4439.88	1	4440.6	2
1, 2, 3, 4, 5, 6..	4435.1	6	4434.4	5	4435.25	3	4435.7	8
	.....	.....	4402.9	1	.....	.....	.....	.....
	.....	.....	4392.6	1	.....	.....	.....	.....
	.....	.....	4383.47	4	.....	.....	4384.0	3
	.....	.....	4371.69	5	4371.70	1	4372.1	4
1, 2, 3, 4, 5, 6..	4349.4	10	4349.91	10	4349.81	15	4350.3	15
5.....	4336.1	2	4335.0	1	.....	.....	.....	.....
	.....	.....	.....	.....	4340.69†	4	4340.9	7
1, 2, 3, 4, 5, 6..	4307.9	9	4307.57	10	.....	.....	4308.3	10
	.....	.....	4296.7	1	.....	.....	.....	.....
	.....	.....	4280.5	1	.....	.....	.....	.....
	.....	.....	4236.4	0	.....	.....	.....	.....

* Visual observations.

† H 4634.20, 4580.2, 4340.60.

TABLE I—*Continued*

Photographic Plate	Wave-length	Int.	Watson	Int.	Royds	Int.	Rutherford and Royds	Int.
5	4226.7	1	4224.2	4	.....	.....	4225.8	2
	.....	.....	4207.4	0	.....	.....	.....	.....
1, 5	4203.5	2	4203.27	10	4203.39	10	4203.7	10
	.....	.....	4193.1	2	.....	.....	.....	.....
	.....	.....	4187.97	4	.....	.....	4188.2	5
	.....	.....	4170.08	3	.....	.....	.....	.....
1, 5	4166.9	3	4166.48	10	4166.59	20	4166.6	20
5	4165.5	1	.....	.....	.....	.....	.....	.....
	.....	.....	4160.57	1	.....	.....	.....	.....
	.....	.....	4114.62	6	4114.71	6	4114.9	7
	.....	.....	.....	.....	.....	.....	4102.2*	6
	.....	.....	4094.4	2	.....	.....	.....	.....
	.....	.....	4088.1	2	.....	.....	4088.4	2
	.....	.....	4073.9	1	.....	.....	.....	.....
	.....	.....	4055.4	2	.....	.....	4055.7	1
	.....	.....	4051.1	2	.....	.....	4051.1	2
	.....	.....	.....	.....	.....	.....	4045.4	4
	.....	.....	4039.5	2	.....	.....	4040.2	1
	.....	.....	4033.9	0	.....	.....	.....	.....
	.....	.....	4017.92	7	4017.90	6	4018.0	10
5	3982.3	2	3981.75	9	3981.83	15	3982.0	12
	.....	.....	3971.82	7	3971.71	8	3971.9	9
	.....	.....	3965.0	2	.....	.....	.....	.....
	.....	.....	3957.32	3	3957.30	8	3957.5	7
	.....	.....	3951.6	2	.....	.....	3952.7	3
	.....	.....	3931.97	2	.....	.....	3933.3	3
	.....	.....	3930.9	0	.....	.....	.....	.....
	.....	.....	3927.1	0	.....	.....	3927.7	1
	.....	.....	3904.9	0	.....	.....	3905.7	2
	.....	.....	3867.68	2	.....	.....	3867.6	4
	.....	.....	.....	.....	.....	.....	3818.0	2
	.....	.....	.....	.....	.....	.....	3811.2	0
	.....	.....	.....	.....	.....	.....	3753.6	10
	.....	.....	.....	.....	.....	.....	3748.6	1
	.....	.....	.....	.....	.....	.....	3739.9	7
	.....	.....	.....	.....	.....	.....	3690.4	2
	.....	.....	.....	.....	.....	.....	3679.2	1
	.....	.....	.....	.....	3664.96	5	3664.6	10
	.....	.....	.....	.....	.....	.....	3650.0	0
	.....	.....	.....	.....	.....	.....	3626.6	2
	.....	.....	.....	.....	.....	.....	3615.4	1
	.....	.....	.....	.....	3612.76	3	3612.2	6
	.....	.....	.....	.....	3122.02	0	.....	.....
	.....	.....	.....	.....	3100.31	1	.....	.....
	.....	.....	.....	.....	3089.15	0	.....	.....
	.....	.....	.....	.....	3005.84	1	.....	.....

* H 4101.9.

only the extreme ends to be photographed alternately. In the first column of the table are given the plates on which each line appears, numbered from 1 to 6. Plates 1 and 2 were obtained from the first spectrum tube, and 3, 4, 5, and 6 from the second tube.

In the table of wave-lengths there have also been recorded, for comparison, along with our results the values determined by Watson and by Rutherford and Royds, since the results of these observers are most trustworthy. Wherever there is coincidence in the lines, the results of the present observations are in excellent agreement with those of the other observers; however, they have recorded many lines which do not appear on our plates. For example, the region between λ 6361 to λ 4732 contains a large number of lines, especially as recorded by Watson, yet our plates show only a few lines in this region and none that could be considered to coincide. It is noteworthy that lines of such great intensity as λ 5582 and λ 5084 should produce no trace on our photographs, nor were these lines observed visually by us.

Among the lines which we observed visually there were several which did not appear on the photographic plates; two of these were broad, faint lines at λ 5058 and λ 4826 respectively, and also a line of low intensity at λ 4735. During the visual observations it was noticed that upon reversal of the current through the induction coil certain lines would appear suddenly and then fade away rapidly. This effect could be produced only after operating the coil as much as 30 minutes in one direction and then reversing the current. The most prominent of these was λ 5483, which appeared very brightly at the moment of reversing the current, but after a few minutes became invisible. It could not be reproduced by later reversals of the current. Other lines appeared brightly at the instant of reversal, but vanished before their wave-lengths could be measured.

Watson has called attention to the differences observed in the intensities of emanation lines; he has also denoted the relative degree of persistence of certain lines in the spectrum. The results of the present experiments have shown that the lines of greatest intensity are the most persistent, and that the intensities of these strong lines change very little on successive plates obtained from the same tube. The group of faint lines between λ 4463 and λ 4492 with one exception were recorded only on the first plate of one tube. On the other hand, there are a number of lines which seem to develop as the time of excitation of the tube advances. For

example, the line λ 4721.2 has an intensity of 1 on the first plate, 4 on the second plate, and 5 on the third plate. The line λ 4625.3 does not appear in the first exposure of either tube, but appears on the second and third plates with increasing intensity. The line λ 4644.0 also belongs to this class. The lines λ 4577, λ 4460, and λ 4307, which Watson has observed to be fugitive lines, for us are quite persistent.

The emanation for these experiments was derived from a supply of radium belonging to the United States Bureau of Mines' Experimental Station at Golden, Colorado.

UNIVERSITY OF DENVER
September 1921

NOTE ON THE MODIFICATION OF DUANE'S APPARATUS FOR PURIFICATION OF RADIUM EMANATION

In 1915, Professor Duane[1] published a method for the purification of radium as collected from aqueous solution, without the use of liquid air. Collection was effected by mercury displacement by means of a system of glass bulbs which acted as an internal pump. In order to remove oxygen and hydrogen from the gaseous mixture, the gases were passed over an electrically heated, partially oxidized copper wire. The glowing wire causes the hydrogen and oxygen to unite, and the excess of hydrogen is reduced by the copper oxide. The water-vapor formed is removed by a side tube containing P_2O_5. The disadvantage in using an oxidized copper wire as the heating body is twofold. On account of the low resistance of copper, a rather high current, 10 to 15 amperes, must be used initially. As the gas pressure diminishes, the current must be correspondingly diminished in order to avoid overheating of the copper wire.

The modification in the furnace consisted in utilizing a platinum wire instead of copper. This has a double advantage in the high melting-point of platinum, and its high resistance. About 5 feet of No. 32 wire was wound on a small rod of silica 5 mm in diameter and 15 cm long. This was then incased in a thin tube of transparent silica fitting snugly over the spiral coil. It was found that sufficient heat was conducted through the quartz tube to raise an oxidized copper ribbon, wrapped spirally outside of the quartz tube, to a sufficient temperature to cause hydrogen to be reduced. By this indirect heating of oxidized copper the temperature was controlled so that there was no danger of overheating the copper, and a very low current, 1 to 3 amperes, was sufficient. Such a furnace was satisfactory for a period of nearly a year without renewal. The copper had to be reoxidized from time to time, as in the original Duane apparatus.

[1] *Physical Review* (2), **5**, 311–314, 1915.

NOTE ON COOLING BY EXPANSION IN SUN-SPOTS[1]

By HENRY NORRIS RUSSELL[2]

ABSTRACT

Cooling by expansion in sun-spots.—Assuming that the low temperature of sun-spots to be due to the expansion of the rapidly rising gases, it is shown that the base of the spot vortex must be a region of very high temperature, probably over 20,000°, and the increase of volume on ascending must be large, probably over 30 times. But only rough estimates can be made.

It is generally accepted that the relatively low temperatures of sun-spots are due to the cooling of the gases by expansion in the upper part of the vortex. The temperature of the spots is probably 2000° to 2500° C., lower than that of the photosphere, so that they may be regarded as the most powerful refrigerating engines known to science.

To estimate the degree of expansion which is necessary to produce this cooling, consider a mass of gas rising in the vortex. It cannot cool faster than the rate given by adiabatic expansion; nor, indeed, nearly as fast, for great quantities of heat are flowing into it by radiation from the hotter regions surrounding the vortex, and, within the gases of the vortex, processes of recombination of electrons with ionized atoms and of formation of chemical compounds are at work on a large scale, and these liberate great quantities of heat. (Formation of TiO_2, 3000 calories per gram of reacting material; neutralization of singly ionized calcium, 3500 calories per gram; most neutralizations give off more heat.)

Meanwhile, the temperature of the surrounding solar gases, through which the vortex column rises, must diminish upward; and this temperature gradient cannot be less than that of radiative equilibrium, for otherwise the observed outward flow of heat from the sun's interior could not be maintained.

In radiative equilibrium, we have

$$T \propto P^{1/4} \propto \rho^{1/3}$$

[1] *Contributions from the Mount Wilson Observatory*, No. 217.

[2] Research Associate of the Mount Wilson Observatory.

where T, P, and ρ represent the temperature, pressure, and density, respectively. In adiabatic expansion:

$$T \propto \rho^{\gamma-1} \propto P^{\frac{\gamma-1}{\gamma}},$$

γ being the ratio of specific heats. The effect of ionization in altering the mean molecular weight of the gases is here ignored.

Suppose that the vortex starts at a depth where the temperature, pressure, and density are T_0, P_0, and ρ_0, and rises to the surface where, outside the spots, these quantities are T_1, P_1, and ρ_1. In the spots, at the visible surface, the temperature will have the lower value T_2. The pressure will be about the same as P_1, for it is probable that we look down through about the same amount of matter per square centimeter, before being stopped by atmospheric scattering, in the spots and in the photosphere; and, of course, the solar gravity is the same.

Hence:

$$P_2 = P_1; \qquad \rho_2 = \frac{T_1}{T_2}\rho_1.$$

We have then for radiative equilibrium:

$$\frac{T_1}{T_0} = \left(\frac{P_1}{P_0}\right)^{1/4},$$

and for adiabatic equilibrium:

$$\frac{T_2}{T_0} = \left(\frac{P_1}{P_0}\right)^{\frac{\gamma-1}{\gamma}};$$

whence:

$$\frac{T_2}{T_1} = \left(\frac{P_1}{P_0}\right)^{\frac{3\gamma-4}{4\gamma}} = \left(\frac{T_1}{T_0}\right)^{\frac{3\gamma-4}{\gamma}},$$

$$\frac{T_0}{T_1} = \left(\frac{T_1}{T_2}\right)^{\frac{\gamma}{3\gamma-4}}; \quad \frac{P_0}{P_1} = \left(\frac{T_0}{T_1}\right)^4; \quad \frac{\rho_0}{\rho_1} = \left(\frac{T_0}{T_1}\right)^3.$$

Now in the actual case T_1 is about 6000°, T_2 3500° to 4000° C., and T_1/T_2 1.5 or more. The greatest possible value of γ is 5/3 (monatomic gas). This would give:

$$T_0 = 2.0T_1 = 12{,}000°; \qquad P_0 = 16P_1; \qquad \rho_0 = 8\rho_1 = 5.3\rho_2.$$

But, for reasons already stated, this must greatly underestimate the amount of expansion. If, as a rough allowance for the effects of radiation and recombination in the ascending vapor, we assume that, on the average, γ equals $7/5$, as for a diatomic gas, we would find:

$$T_0 = 17T_1 = 100{,}000^\circ; \quad P_0 = 80{,}000P_1; \quad \rho_0 = 5000\rho_1 = 3300\rho_2.$$

Assuming $\gamma = 3/2$, we have:

$$T_0 = 3.7T_1 = 22{,}000^\circ; \quad P_0 = 190P_1; \quad \rho_0 = 51\rho_1 = 34\rho_2.$$

It is evident, therefore, that the base of the spot vortex must be in a region of high temperature, and that the increase of volume in ascending must be great; but no numerical estimates can be made.

It may be noticed in conclusion that the very existence of cooling by expansion in sun-spots shows that any general vertical convection in the outer layers of the sun must either reach only to a depth which is small compared with that from which the ascending spot vortex comes, or else be so slow that the cooling by expansion as the gases rise is continuously made up by heating by radiation. Otherwise the temperature gradient would be so nearly adiabatic that no important differential cooling could occur in the spots.

MOUNT WILSON OBSERVATORY
July 27, 1921

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THE EDITORS